Naval Information Warfare Center PACIFIC

TECHNICAL REPORT 3185
November 2019

Development of a Compact Wind and Water Mitigation System for Deployment of Infrasound Sensors on Unmanned Surface Vehicles

Randall Plate
Doug Grimmett

Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001

This page intentionally blank.

TECHNICAL REPORT 3185
November 2019

Development of a Compact Wind and Water Mitigation System for Deployment of Infrasound Sensors on Unmanned Surface Vehicles

Randall Plate
Doug Grimmett

Administrative Notes:
This report was authored in September 2018, approved through the Release of Scientific and Technical Information (RSTI) process in October 2018, and formally published in the Defense Technical Information Center (DTIC) in November 2019.

This report's content represents work performed under Space and Naval Warfare Systems Center Pacific (SSC Pacific). SSC Pacific formally changed its name to Naval Information Warfare Center Pacific (NIWC Pacific) in February 2019.

SPAWAR Systems Center PACIFIC
Naval Information Warfare Center PACIFIC
UNITED STATES NAVY

NIWC Pacific
San Diego, CA 92152-5001

NIWC Pacific
San Diego, California 92152-5001

M. K. Yokoyama, CAPT, USN
Commanding Officer

W. R. Bonwit
Executive Director

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Advanced Research branch (56490) of the Autonomous Technologies division under the Intelligence, Surveillance & Reconnaissance department (56) at Naval Information Warfare Center Pacific (NIWC Pacific), San Diego, CA, known at the time of this work as the Space and Naval Warfare Systems Center Pacific (SSC Pacific). The work was performed as part of the Maritime Infrasound Monitoring (MIM) project, a Technology Transition project funded under the Naval Innovative Science and Engineering (NISE) program at SSC Pacific. We would like to acknowledge NASA Langley Research Center for their support to conduct this testing at their facility, and Dr. Qamar Shams for providing and operating the NASA microphones, windscreens, infrasound sources, and data acquisition equipment.

Released by
Thomas L. Jones, Head
Advanced Research Branch

Under authority of
Mark Berry, Head
Autonomous Technologies Division

RJP

EXECUTIVE SUMMARY

OVERVIEW

This report was completed for the Maritime Infrasound Monitoring (MIM) project. One objective of the MIM project at the time testing was done for this report was to develop a unique windscreen design for deployment with an infrasound sensor aboard a small, unmanned surface vehicle (USV). The unique windscreen must possess several specific capabilities/features: it must (1) reduce wind noise, (2) provide protection from water, and (3) be suitably compact for deployment on a Liquid Robotics SV2/3 USV. This report documents the results of a test performed to evaluate potential windscreen designs that address these requirements.

WINDSCREEN TECHNOLOGIES EVALUATED

The NASA Langley Research Center developed a windscreen using closed-cell foam that may meet all three requirements of the windscreen being pursued for use under the MIM project. However, previous conflicting reporting led to uncertainty of whether these attenuated the source signal and/or provided the claimed wind mitigation. A side-by-side test event was performed at NASA Langley in Hampton, VA from April 13–20, 2018 to investigate the performance of various infrasound sensors and windscreens. The premise for the test was primarily to investigate the performance of the closed-cell foam windscreens being developed by NASA in terms of transmissivity and wind noise reduction. Additionally, as part of this research, other compact windscreens were evaluated to provide comparison points. These alternative windscreens consisted of two perforated metal windscreens (tent and cylinder) from Army Research Lab, a trampoline fabric tent windscreen from Hyperion Technology Group, and a perforated metal colander provided by SSC Pacific. In addition to the windscreens, two different infrasound sensors were evaluated: an electret microphone being produced for NASA by PCB Piezotronics, and a piezoelectric microbarometer produced by Hyperion. NASA provided multiple microphone setups with closed-cell foam windscreens and back chambers. SSC Pacific provided two Hyperion microbarometers and one closed-cell foam windscreen with back chamber for this unit.

RESULTS

The results of our testing show that the closed-cell foam windscreens do not attenuate the infrasound signal, provided a properly designed back chamber is used; improper venting results in signal attenuation.

Both versions of the closed-cell foam windscreens (those designed for use with NASA microphone and Hyperion microbarometer) demonstrated good wind mitigation performance. However, the tent style windscreens demonstrated slightly better wind mitigation performance at the source frequencies used for this test.

Overall, this test was successful in providing sufficient insight into the closed-cell foam windscreen performance that further pursuit of such a solution for our application is warranted. Note: there are remaining questions of performance in different environments, and with different designs that are more suitable to a maritime installation (such as more compact shapes and venting configurations to other mediums than the ground) that will need to be investigated.

This page is intentionally blank.

ACRONYMS

3OS	Third Offset Strategy
ARL	Army Research Laboratory
BAR	Basic and Applied Research
B&K	Bruel & Kjaer
CCF	Closed-Cell Foam
MIM	Maritime Infrasound Monitoring
NASA	National Aeronautics and Space Administration
NISE	Naval Innovation Science and Engineering
NOWS	No Windscreen
SV2	Surface Vehicle 2
TT	Technology Transition
USV	Unmanned Surface Vehicle

This page is intentionally blank.

CONTENTS

EXECUTIVE SUMMARY .... **v**
ACRONYMS .... **vii**
1. BACKGROUND AND MOTIVATION **1**
1.1 CHALLENGES 1
1.2 PRIOR NONPOROUS WINDSCREEN INVESTIGATION 2
1.3 WIND MITIGATION EVALUATION 2
2. EQUIPMENT **5**
2.1 SENSORS 5
2.1.1 NASA Electret Microphone 5
2.1.2 Hyperion Microbarometer 6
2.2 WINDSCREENS 7
2.2.1 Closed-Cell Foam Windscreens 7
2.2.2 Perforated Metal Windscreens 9
2.2.3 Tent Style Fabric Windscreen 10
2.3 OTHER EQUIPMENT USED 10
2.3.1 Infrasound Sources 11
2.3.2 Ultrasonic Anemometer 11
2.3.3 B&K Data Acquisition System 12
2.3.4 B&K Microphones 12
3. EXPERIMENT DESCRIPTION **14**
3.1 LABORATORY TESTING 15
3.2 FIELD TESTING 15
4. EXPERIMENT RESULTS **17**
4.1 SENSOR CALIBRATION 17
4.2 CLOSED-CELL FOAM WINDSCREEN TRANSMISSIVITY 18
4.3 SNR ANALYSIS 20
4.3.1 NASA Microphone with Various Windscreens 22
4.3.2 NASA Microphone with CCF vs. Hyperion Microbarometer NOWS 23
4.3.3 Hyperion Microbarometer with Various Windscreens 24
4.3.4 Hyperion with Acorn Shroud 26
4.3.5 Venting of Closed-Cell Foam Windscreens 27
4.4 SPECTRAL ANALYSIS 32
4.4.1 Broadband Wind Mitigation 32
4.4.2 Transmissivity Using Source Sweeps 35
4.4.3 Jet vs. Wind Noise 37

5. CONCLUSIONS.......... 39
5.1 LESSONS LEARNED 39
5.2 FUTURE STEPS 40
REFERENCES.......... 41

APPENDICES

A: ADDITIONAL DATA **A-1**

Figures

1. SV2 Waveglider with infrasound sensor package installed. 1
2. PCB Piezotronics microphone and power supply, per NASA's design. 6
3. Hyperion IFS-5311 microbarometer. 6
4. Comparison view of various windscreens used in testing. ...From left to right: ARL metal tent, ARL metal cylinder, Hyperion trampoline fabric tent, SSC Pacific CCF hemisphere, NASA CCF sphere, NASA CCF box. 7
5. NASA CCF windscreens: box configuration (a), back chambers and microphones without windscreens (b), and complete back chamber with spherical windscreen (c) 8
6. Hyperion microbarometer on base for hemisphere (left) and with hemisphere windscreen installed (center). Diagram of the windscreen assembly (right). 8
7. Hyperion microbarometer with remote acorn intake and closed-cell foam windscreen for USV installation (left) and with grounded back chamber as tested at NASA (right). 9
8. ARL perforated metal windscreens: tent style (left) and cylinder (right). 9
9. SSC Pacific improvised perforated metal windscreen. 10
10. Hyperion trampoline fabric tent windscreen 10
11. Infrasound sources used at NASA, Langley: 2 laboratory sources (tops Labsources 1 and 2) and 2 outdoor field sources (bottom, field sources 1 and 2) 11
12. Gill ultrasonic anemometer and mounting base 12
13. B&K 2270 with 4189 microphone with spherical open-cell foam windscreen and 8103 hydrophone. 13
14. Outdoor field test layout at NASA Langley 16

15. Comparison of NASA microphone and Hyperion microbarometer with no windscreens. 17

16. Spectral comparison of NASA microphone and Hyperion microbarometer with no windscreens from Test 22 18

17. SNR comparison of NASA microphone with 15 lb. CCF windscreen vs. NOWS in the lab to evaluate transmissivity. 19

18. Spectrum of NASA microphone with CCF sphere windscreen (left) and zoomed in portion showing 2 dB loss at tone at 9 Hz (right) from Test 22 19

19. Example of signal and noise estimates from 5-minute test spectrum. 20

20. Scatter plot of all field measurements containing 6 and 9 Hz tones for each sensor/windscreen combination. Sensors are indicated by ‘x’ (NASA microphone) or ‘o’ (Hyperion microbarometer); windscreens are indicated by color. 21

21. Summary of relative SNR performance for all sensor/windscreen combinations tested. NOWS configurations shown in beige, closed-cell foam in blue, metal and fabric windscreens in green, and combination of closed-cell foam with cylinder in yellow. 22

22. SNR comparison of NASA microphone with no windscreen, closed-cell foam windscreen, and other windscreens: ‘MC’ = Metal Cylinder, ‘MT’ = Metal Tent, ‘TT’ = Trampoline Tent. The CCF windscreen (yellow) used was 15 lb. for 33-36 and 30 lb. for 37-45. 23

23. SNR comparison of NASA microphone with 18 lb. closed-cell foam windscreen vs. NOWS Hyperion microbarometer. 24

24. SNR comparison of Hyperion microbarometer with closed-cell foam hemisphere vs. NOWS. 25

25. SNR comparison of Hyperion microbarometer with colander windscreen vs. NOWS. 25

26. SNR comparison of Hyperion microbarometer with perforated metal and fabric tent windscreens vs. NOWS: ‘MC’ = Metal Cylinder, ‘MT’ = Metal Tent, ‘TT’ = Trampoline Tent. 26

27. SNR analysis of Hyperion microbarometer with acorn shroud vs. NOWS Hyperion vs. NASA microphone with CCF windscreen. Acorn configurations are: no windscreen (NOWS), closed-cell foam sphere (CCF), and closed-cell foam sphere inside the perforated metal cylinder (CCF+MC). 27

28. Comparison of different venting and back chamber configurations for the Hyperion sensor with CCF hemisphere windscreen in the lab. Test

configurations: “NV” = no vent, “F” = foam, “B” = bubble wrap, “P” = popsicle stick 28

29. Power spectra of non-vented CCF hemisphere vs. NOWS microbarometer (left) and difference spectra of various configurations of hemisphere back chamber vs. NOWS microbarometer (right). 29

30. Different venting configurations evaluated in the field: Test 61 in tray of water (left), Test 62 in tray of water with air gap (center), and Test 63 spaced off ground on wood blocks (right). 30

31. Comparison of different venting configurations for the Hyperion sensor with closed-cell hemisphere windscreen in the field. Legend for test cases: “Std” = standard venting to ground, “H2O” = venting to water bath, “H2O+Spacer” = water bath with spacer, “Blocks” = spacing the entire assembly off the ground on blocks, “Taped” = taping over the vent hole (non-vented case). 31

32. Power spectra for outdoor hemisphere venting comparison: no windscreen, standard vent to ground, no vent (sealed), vent to water, and suspended on blocks. 32

33. Difference spectra of NASA microphone with and without a windscreen for test 28 (Top) and Test 29 (bottom) 33

34. Spectra of Hyperion microbarometer with closed-cell foam hemisphere compared to other windscreens (left) and difference spectra between hemisphere and other windscreens for each test (right): closed-cell foam box (right, 1st), metal cylinder (right, 2nd and 3rd), trampoline tent (right, 4th and 5th) 33

35. Comparison of NASA 15 lb. closed-cell foam windscreen to other windscreens 34

36. Comparison of NASA 30 lb. closed-cell foam windscreen to other windscreens 35

37. Power spectral densities for NASA and Hyperion sensors both with and without closed-cell foam windscreens for linear frequency sweep (Test 13) 36

38. Difference power spectral densities for NASA and Hyperion sensors both with and without closed-cell foam windscreens for linear frequency sweep (Test 13) 36

39. Power spectral densities of test examples comparing segments of jet take-offs with ambient; low wind cases (left) and higher wind cases (right). 37

1. BACKGROUND AND MOTIVATION

Maritime Infrasound Monitoring (MIM) is a Naval Innovation Science and Engineering (NISE) Technology Transition (TT) project at Space and Naval Warfare Systems Center Pacific (SSC Pacific) focused on maturing the technological capability of deploying infrasound sensors on small, unmanned surface vehicles (USVs) in the maritime environment. It is a follow-on effort to a previous NISE Basic and Applied Research (BAR) project that was funded from FY14–FY17. The MIM project received its first year of funding in FY18. For FY19, funding will be jointly provided by the SSC Pacific NISE program and PMS-485 via the Third Offset Strategy (3OS) program.

1.1 CHALLENGES

The previous BAR project developed a preliminary capability of integrating a microbarometer infrasound sensor onto a Liquid Robotics SV2 Wave Glider. This sensing system was deployed multiple times at sea with varying levels of success and lessons learned. One of the key limiting factors was the challenge of keeping water out of the sensor, yet allowing it to remain sensitive to fluctuations in air pressure (the signals of interest). Preliminary testing has shown that salt water entering the sensor can not only damage the sensor if it is not designed to be robust to this, but also affects data quality due to water drops creating glitches when they impact the sensor piezoelectric disks.

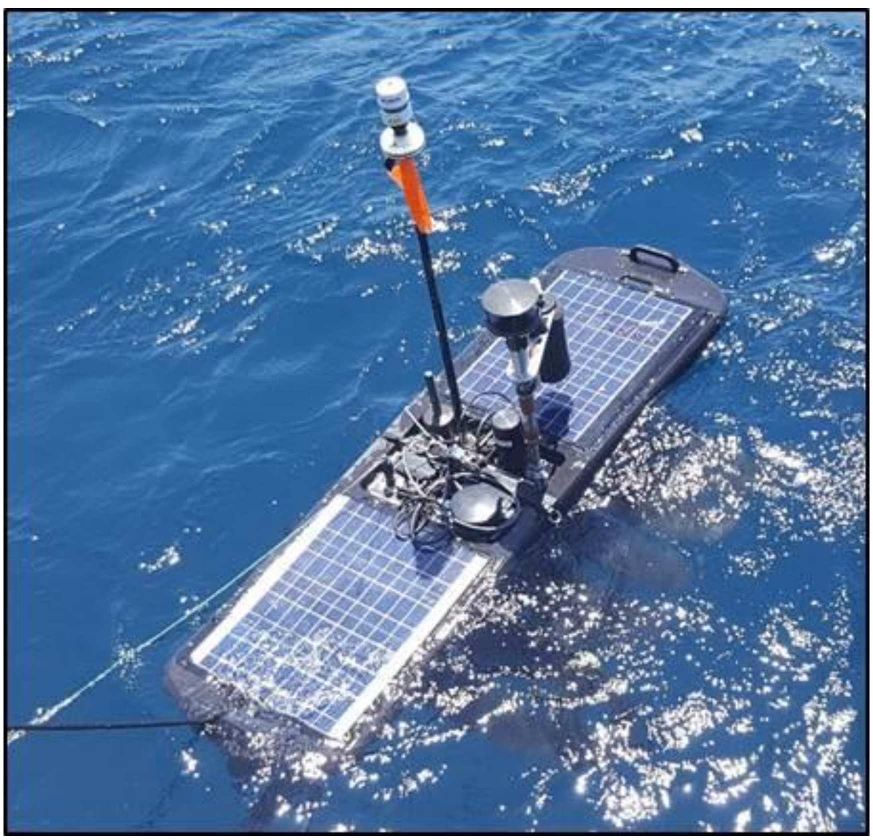

Figure 1. SV2 Waveglider with infrasound sensor package installed.

A second challenge is wind mitigation, as noise produced from wind impacting the sensor is a significant component of the background noise in the infrasound band of interest. Typical wind mitigation approaches for infrasound sensors require large structures consisting of rosette pipe arrays or large barriers in the form of domes or fences. Efforts at designing compact wind screens are being performed by numerous researchers, mostly consisting of fabric or metal structures that surround the sensor. Even these are potentially too large for a sensor mounted on a small USV. We discovered a unique wind mitigation approach being developed at NASA Langley Research Center that is based on closed-cell foam (CCF) spheres. These are the most compact windscreens we have found, with a spherical diameter of about one foot. The closed-cell foam is unique in that the material is impermeable to both water and air, enabling complete protection from the environment.

1.2 PRIOR NONPOROUS WINDSCREEN INVESTIGATION

The development of the theory behind the nonporous windscreens being developed at NASA is provided in [1] for various potential shapes, including cubes and spheres. Preliminary test results for experiments based on this theory are provided in [2, 3], which report that transmissivity coefficients greater than zero are achievable below 20 Hz for properly chosen materials. In addition, wind noise reduction of up to 20 dB was demonstrated in the infrasound band.

However, other independent evaluations of the closed-cell foam windscreens reported some concerns over their performance in terms of transmissivity and wind mitigation. Army Research Laboratory (ARL) performed a laboratory test in 2013, which compared pink noise recorded on a NASA microphone with CCF windscreens of various densities to a reference Bruel & Kjaer (B&K) microphone [4]. They concluded that significant attenuation of up to 20 dB was caused by the windscreens, unless a relief valve was opened up, in which case the acoustic noise simply passed through the valve and wind mitigation would be ineffective. However, this test setup used an older version of the microphone stand that did not include a back chamber; the relief valve simply vented to the environment. Since this time, it has been determined that a properly designed back chamber that simultaneously provides venting and isolation from the ambient environment is crucial to maintaining good performance of the CCF system (no attenuation and good wind mitigation).

A second comparison of nonporous windscreens is presented in [5], which involved a cubic windscreen of similar design to that proposed by NASA, and an “optimized” windscreen constructed by the Université de technologie de Compiègne. The conclusion drawn was that the cubic windscreen attenuated the signal by 14 dB, but their optimized windscreen demonstrated no attenuation. However, there is no discussion of a venting scheme used for the cubic windscreen, so this is again different from the most recent iteration of NASA’s microphone/windscreen setup.

1.3 WIND MITIGATION EVALUATION

As discussed in the technical challenges described above, we are working to develop a windscreen that meets three performance criteria: sufficient wind mitigation, sufficient water mitigation, and a sufficiently compact size to mount on a small USV. The NASA closed-cell foam windscreens potentially meet all three of these, but due to the conflicting reports on the performance, additional testing was required to validate performance and determine whether further consideration was warranted.

One of the main efforts undertaken during this year of funding was to perform a side-by-side test at NASA Langley of both their sensor (an electret infrasound microphone) and windscreen and our existing sensor (a piezoelectric microbarometer) with CCF windscreen as well as various other compact windscreens of different designs. The goal of this test was to evaluate the wind mitigation performance of the most recent configuration of the closed-cell foam windscreens with respect to other wind mitigation options, and whether they show promise to meet our needs of both water and wind mitigation. Even if the wind mitigation properties of the closed-cell foam windscreen are not optimal, “sufficient” performance in this area may be acceptable if the other two criteria are satisfied, because these are non-negotiable in order to provide valid infrasound data from our desired maritime platform and other solutions investigated so far have not proven to be robust.

This report documents the equipment used, a description of how the testing was performed, the results of the testing, and the conclusions and impacts on the future direction of the project.

This page is intentionally blank.

2. EQUIPMENT

The equipment under test consisted of both infrasound sensors and windscreens. In addition, various other equipment was used to facilitate testing including a Bruel & Kjaer (B&K) data acquisition system, multiple infrasound sources provided by NASA Langley, and an ultrasonic anemometer to accurately measure local wind speed and direction.

2.1 SENSORS

Two different infrasound sensors were evaluated during this test: an electret microphone designed by NASA and manufactured by PCB Piezotronics, and a piezoelectric microbarometer produced by Hyperion Technology Group. A comparison of various technical specifications of these sensors is shown in Table 1.

Table 1. Technical specifications of the two infrasound sensors tested.

	PCB Piezotronics 377M19 Microphone	Hyperion IFS-5000 Microbarometer
Nominal Sensitivity	370 mv/Pa	70 mv/Pa
Dynamic Range	115 dB	140 dB (10^{-5} – 100 Pa)
Frequency Response	< 3 dB variance from 0.01-350 Hz	< 3 dB variance from 0.01-100 Hz
Power Consumption	35 mW	1.5 W

2.1.1 NASA Electret Microphone

NASA has worked with PCB Piezotronics to produce an electret infrasound microphone meeting NASA's design specifications. This microphone has a large diameter diaphragm (3") with high compliance (low tension) which results in a low bandwidth but high sensitivity, suitable for measurements in the infrasound band [3]. The large diaphragm also reduces the impact of 1/f noise on the microphone. In addition, the microphone features a large back chamber so that the series compliance is controlled by the diaphragm rather than the air layer.

Figure 2. PCB Piezotronics microphone and power supply, per NASA's design.

2.1.2 Hyperion Microbarometer

Hyperion Technology Group is a commercial company that produces an infrasound sensor using piezoelectric sensing elements [6]. The IFS-5000 series, used for this test, contains two sets of disks mounted with opposite polarity enabling seismic decoupling. This allows the sensor to reject signals produced by small vibrations while remaining sensitive to acoustic signals, or vice versa.

As will be seen in the results of the testing, the high frequency shroud (lower half of the sensor with holes around the circumference, as pictured in Figure 3) inherently rejects wind noise to some extent, yielding better signal-to-noise ratios with no external windscreen than the NASA microphone.

Figure 3. Hyperion IFS-5311 microbarometer.

2.2 WINDSCREENS

The primary focus of this investigation was on the compact, closed-cell foam windscreens developed by NASA. The performances of these windscreens were compared to various alternative compact windscreen concepts provided by Army Research Lab (ARL) and Hyperion.

Figure 4. Comparison view of various windscreens used in testing. From left to right: ARL metal tent, ARL metal cylinder, Hyperion trampoline fabric tent, SSC Pacific CCF hemisphere, NASA CCF sphere, NASA CCF box.

2.2.1 Closed-Cell Foam Windscreens

These windscreens differ from most other windscreens being used or developed by being impermeable to air. They are constructed using ½" thick polyurethane, closed-cell foam. To enable the acoustic energy to transfer through the windscreen without attenuation, a properly designed base is required that enables the spherical windscreen to vent into a back chamber that is isolated from the ambient environment. NASA's current back chambers use the ground to provide a means of pressure release while maintaining isolation between the interior of the windscreen and the outside environment. A back chamber design that does not require the ground in this way would need to be developed in order to use the system in our USV application.

Several implementations of these windscreens were tested, most of which were designed and manufactured by NASA. These include a rectangular box and spherical shapes with varying densities of foam (15-lb., 18-lb., and 30-lb.). Higher foam densities provide better wind mitigation performance, but also have a lower cutoff frequency where acoustic signals begin being attenuated. The rectangular box was designed to be buried in the ground, but was not installed as of the time of this test. Thus, the results for this windscreen are not optimal and are not focused on in the analysis provided.

(a)	(b)	(c)

Figure 5. NASA CCF windscreens: box configuration (a), back chambers and microphones without windscreens (b), and complete back chamber with spherical windscreen (c)

SSC Pacific also provided two implementations of closed-cell foam windscreens based on NASA's design, but suitable for use with the Hyperion microbarometer sensor. This is the first time, to our knowledge, that the Hyperion sensor has been tested with such a windscreen. For both versions, a back chamber that approximates that used with the NASA microphone was constructed prior to the test by SSC Pacific.

The first implementation is a hemisphere that encloses the entire microbarometer (Figure 6). This hemisphere is mounted to an aluminum disk to which the hemisphere seals with a rubber O-ring. During testing, a small hole was made through the aluminum into a back chamber made of 8" diameter PVC with ¼" wall thickness to enable venting.

Figure 6. Hyperion microbarometer on base for hemisphere (left) and with hemisphere windscreen installed (center). Diagram of the windscreen assembly (right).

Another, spherical version was also made that fits around an alternative acorn-shaped intake that connects to the microbarometer via a flexible plastic tube, as shown in Figure 7. This acorn design was constructed by Hyperion in an effort to prevent water intrusion into the sensor for our USV-based deployment, as it enables the sensor canister to be sealed from water and the acorn to be mounted higher off the platform out of water's reach. However, it introduces some acoustic anomalies and complications, and therefore the hemisphere design is our primary interest currently.

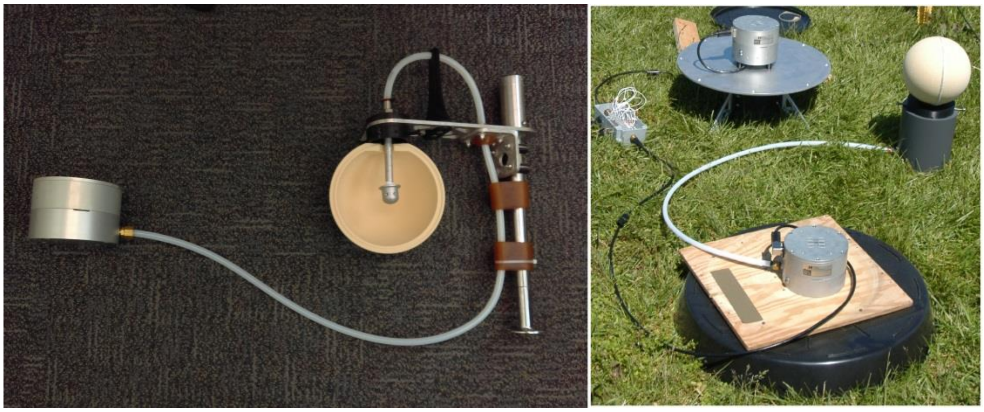

Figure 7. Hyperion microbarometer with remote acorn intake and closed-cell foam windscreen for USV installation (left) and with grounded back chamber as tested at NASA (right).

2.2.2 Perforated Metal Windscreens

Army Research Lab has been researching compact infrasound windscreens and provided two of their most recent designs on loan to be included in this test. They both are constructed of similar perforated metal, and thus allow air to pass through the windscreen but reduce wind noise by altering the airflow. One is a 12-sided tent shape, and the other a cylinder with closed (perforated) top. Both windscreens have the bottom side open to the ground.

Figure 8. ARL perforated metal windscreens: tent style (left) and cylinder (right).

Prior to this investigation, SSC Pacific had been using an improvised perforated metal windscreen constructed out of a large cooking colander. This windscreen was included in two tests to evaluate how well it compares to more properly designed windscreens. In one test it was lined with felt, and in the other the felt was omitted.

Figure 9. SSC Pacific improvised perforated metal windscreen.

2.2.3 Tent Style Fabric Windscreen

SSC Pacific purchased a fabric tent style windscreen for this test produced by Hyperion that is made using trampoline fabric stretched over a collapsible frame. Once again, this material is permeable to air, but the holes are much finer than those in the ARL perforated metal windscreens.

Figure 10. Hyperion trampoline fabric tent windscreen

2.3 OTHER EQUIPMENT USED

There was auxiliary equipment required to conduct the testing of sensors and windscreens, including infrasonic sources, reference sensors, and data acquisition system.

2.3.1 Infrasound Sources

NASA has constructed several infrasound generators, which were used both in the lab and in the field to produce source tones of known, steady amplitude and frequency. The sources used in the lab each consist of a large subwoofer cabinet driven by an audio amplifier that is fed a tone from a signal generator. These were operated at 9 Hz and 18 Hz simultaneously for most test events. Each of the sources used in the field have a cylindrical shaped cavity that is connected to a large subwoofer. Again, the subwoofer is driven by an audio amplifier that is fed a tone from a signal generator. These were operated at 6 Hz and 9 Hz simultaneously for most test events.

Figure 11. Infrasound sources used at NASA, Langley: 2 laboratory sources (top) and 2 outdoor field sources (bottom)

2.3.2 Ultrasonic Anemometer

A Gill WindSonic M ultrasonic anemometer was deployed for all of the field measurements to record accurate wind speed and direction. This information was used to correlate background noise levels observed to the wind speeds present in order to characterize the windscreen performances in different wind levels. As no artificial wind sources were used (fans), we were limited to what the weather provided which ranged from low to medium wind. This anemometer was configured to sample both wind speed and direction at 4 Hz. The anemometer was mounted on a plywood base with the sensing elements located approximately 18 inches off the ground.

Figure 12. Gill ultrasonic anemometer and mounting base

2.3.3 B&K Data Acquisition System

All data from the infrasound sensors and anemometer was recorded using a B&K data acquisition system consisting of two PULSE units. The first was configured with six channels (model 3050-A-060), and second with four (model 3050-A-040), for a total of 10 input channels.

2.3.4 B&K Microphones

During the outdoor measurements, a separate B&K 2270 handheld recorder was operated as a constant recording device with no windscreen changes. The integrated microphone on the recorder was a type 4189 and was fitted with the standard B&K open-cell foam spherical windscreen. Channel 2 of the recorder was connected to a type 8103 hydrophone in order to compare the wind sensitivity of the microphone with windscreen to that of the hydrophone.

Figure 13. B&K 2270 with 4189 microphone with spherical open-cell foam windscreen and 8103 hydrophone.

This page is intentionally blank.

3. EXPERIMENT DESCRIPTION

Data was collected in two different environments as part of the side-by-side testing: a controlled lab environment and an outdoor field where wind was present. The entire test duration was one week, from April 13–20. During this time, 67 different test events were conducted, each consisting of 5–10 minutes of data collection with a set of sensors and windscreens.

3.1 LABORATORY TESTING

Testing was first performed in a controlled lab environment on the first three days (April 13, 16, and 17) to compare performance of sensors and windscreens without the interference of wind noise. The objectives were:

- Comparison of sensitivities and frequency responses of all NASA microphones vs. the Hyperion microbarometers without windscreens
- Evaluation of sensitivities of each sensor to vertical displacement and flip motion
- Evaluation of transmissivities of the various closed-cell foam windscreen implementations
  - Including iteration of configuration of hemisphere (modifying venting and internal volume)

For most of the lab testing, two different infrasound sources were used in the lab, simultaneously, to produce sinusoidal tones at 9 and 18 Hz.

3.2 FIELD TESTING

The majority of testing was performed in the field in order to evaluate the performance of the different windscreens in the presence of wind. The objectives were:

- Magnitude and spectrum of wind noise for each sensor with no windscreen
- Magnitude and spectrum of wind noise for each sensor/windscreen combination
- Signal-to-noise ratio (SNR) obtainable for each sensor/windscreen combination

A birds-eye view of the test field is shown in Figure 14. On April 18, sensors were nearly collocated near sensor position 1 (North-most position). The evening of April 18, two NASA microphones (with windscreens) were moved to positions 2 and 3 in order to set up an array for overnight data collection. They remained in these positions during the following two days of testing.

Figure 14. Outdoor field test layout at NASA Langley

For most of the field testing, two different infrasound sources were used to produce sinusoidal tones of 6 and 9 Hz, simultaneously.

4. EXPERIMENT RESULTS

Each test event was five minutes long with constant source frequencies during the duration (with the exception of tests 12 and 13, as discussed in Section 4.4.2. Frequency spectra were produced for each test event. Additionally, for all test events involving infrasound sources, the peak level of each tone was detected and recorded, in addition to a measurement of the noise adjacent in frequency to each tone. From these measurements, a signal-to-noise ratio (SNR) was computed to provide a metric to compare different source/windscreen performance within each test.

For these test results, “NOWS” refers to a sensor with “no windscreen”. Closed-cell foam windscreens will be abbreviated “CCF”.

4.1 SENSOR CALIBRATION

Prior to comparing windscreens, the different sensors were compared to each other to evaluate calibration and any differences in frequency response. As shown in Figure 15, source tones at 9 and 18 Hz were generated in the lab and measurements were made of the signal level at these tones (top row), the background noise level surrounding the tones (middle row), and a signal-to-noise ratio (bottom row). Results are shown for seven independent test events (10, 11, 14, 22, 23, 24, and 25). Initial tests (prior to test 14) show a calibration difference between NASA sensors and the Hyperion sensors on the top, signal level plots. This was resolved by refining the sensitivity numbers used in the data acquisition software for each specific sensor, rather than nominal numbers. This is evident in the agreement of all three plots (signal, noise, and SNR) for tests 14 and following. The spectrum in Figure 16 shows this across the entire infrasound and, with less than 1 dB difference at all frequencies of interest above 0.2 Hz. The sensors do diverge in response at the lower frequency range below 0.2 Hz, with the NASA sensor producing a lower output than the Hyperion.

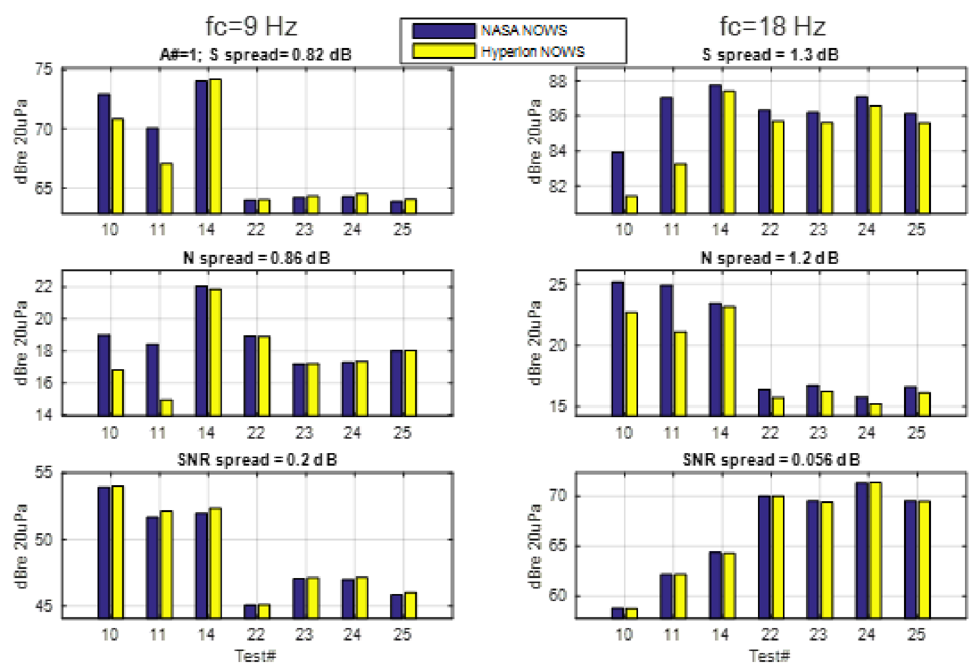

Figure 15. Comparison of NASA microphone and Hyperion microbarometer with no windscreens.

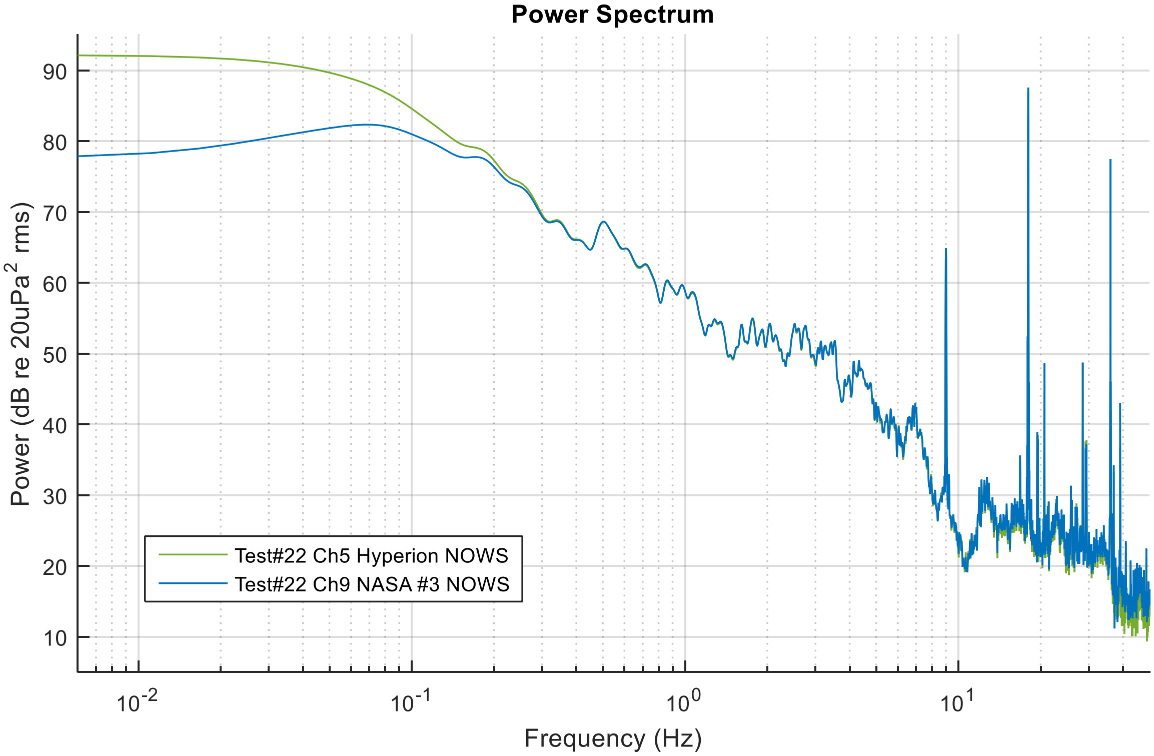

Figure 16. Spectral comparison of NASA microphone and Hyperion microbarometer with no windscreens from Test 22

While these results show good calibration agreement, later testing outdoors yields varying signal levels, leading to uncertainty in the absolute levels obtained for some tests. We had various technical difficulties with the data acquisition computer, and had to switch to a different computer at times, so it is possible that the calibrations were not transferred properly when these swaps occurred. This has caused us to be cautious about making comparisons of absolute levels between different sensors or between different tests. However, the computed signal-to-noise ratios will be valid regardless of calibration, so these numbers are more heavily trusted.

4.2 CLOSED-CELL FOAM WINDSCREEN TRANSMISSIVITY

In lab testing of the NASA microphone with 15 lb. closed-cell foam sphere compared to a NASA microphone without any windscreen, there is a 2 dB loss observed at 9 Hz and 7 dB loss at 18 Hz (top two plots in Figure 17). It is observed in Figure 18 that the frequency responses are very similar at the lower end of the spectrum, aside from a slight gain below 0.1 Hz, and diverge as frequency gets higher due to the well-known low pass characteristic of the closed-cell foam [2]. This is a function of the density of the foam used, with higher density foam rolling off at a lower frequency; the results shown here are for 15 lb. density. It is unknown why the noise levels are not uniformly attenuated like the signals are at 18 Hz (middle right plot in Figure 17). This appears to indicate that there are sources of noise that enter the microphone that are not propagating through the windscreen, but instead, perhaps are coupling or propagating through the back chamber/stand.

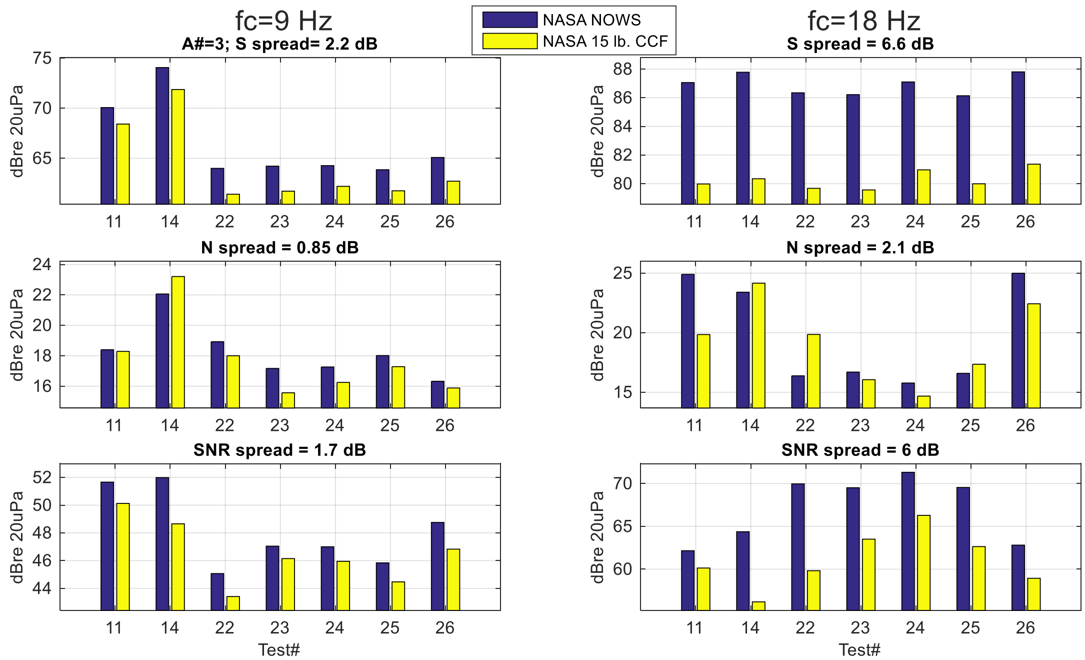

Figure 17. SNR comparison of NASA microphone with 15 lb. CCF windscreen vs. NOWS in the lab to evaluate transmissivity.

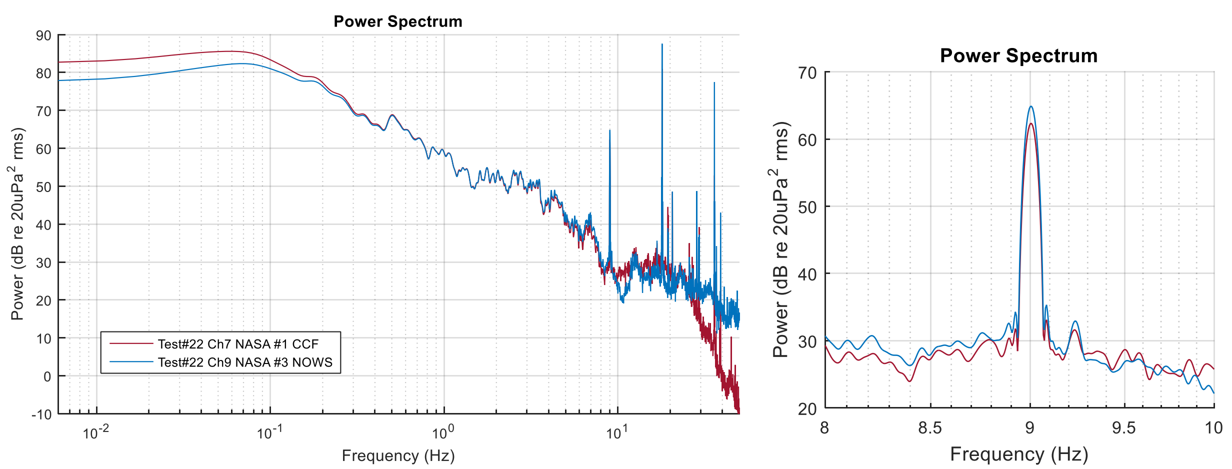

Figure 18. Spectrum of NASA microphone with CCF sphere windscreen (left) and zoomed in portion showing 2 dB loss at tone at 9 Hz (right) from Test 22

In contrast, the field measurements actually show a gain of approximately 2 dB for a microphone fitted with either a 15 or 30 lb. CCF windscreen at both 6 and 9 Hz (see Figure 22 in the next section). It is uncertain why this gain would be present outside in the presence of wind, but not in the lab; it is also possible that this was a calibration issue once we moved the equipment outside. This would need to be investigated in further testing to identify. However, it is not critical to interpreting the remainder of the results presented in this analysis.

4.3 SNR ANALYSIS

For the SNR analysis, frequency spectra using the entire 5 minutes of data for each test were created. From these spectra, tone peak level (signal) and noise level were estimated, an example of which is shown in Figure 19. From these measurements, an SNR estimate was computed for each source tone in each test.

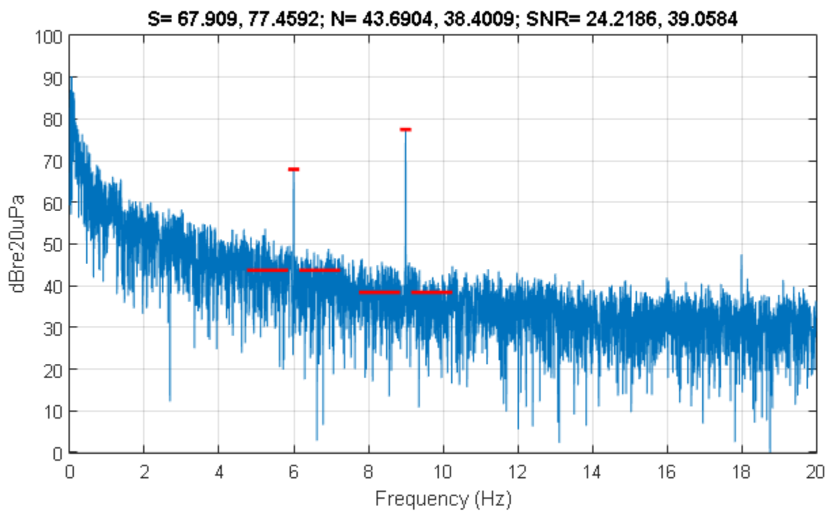

Figure 19. Example of signal and noise estimates from 5-minute test spectrum.

In addition, the average wind speed for each 5-minute test was computed. A scatter plot showing the SNR vs. average winds speed for all of the field measurements made using the primary windscreens of interest is shown in Figure 20 (some tests of special cases or auxiliary windscreens have been omitted for clarity). It can be noted that more low wind measurements were obtained than higher wind, and that even the highest average wind measured is less than 4 m/s. Also, there are not an equal number of test cases for each configuration, which can skew the impression gleaned from the plot. Analyses presented later will provide the opportunity for more precise comparisons. However, a clear trend between decreasing SNR with increasing wind speed is observed for all windscreens tested.

Clearly, the lowest SNR values are observed with the NOWS cases (blue), and of these, the NASA sensor is significantly lower than the Hyperion for equal wind speed. There were no test cases with a NASA microphone without a windscreen in higher wind. The highest SNR values are observed with the trampoline fabric tent windscreen (yellow). The other ARL windscreens (purple and green) also perform better in general than the closed cell foam (red) at these specific frequencies. However, there are also cases where the closed cell foam yields better SNR, indicating that it is a viable windscreen option, and may perform better in certain conditions. The metal/fabric windscreens used in conjunction with the Hyperion sensor more often yield higher SNR than the same windscreen used with the NASA microphone.

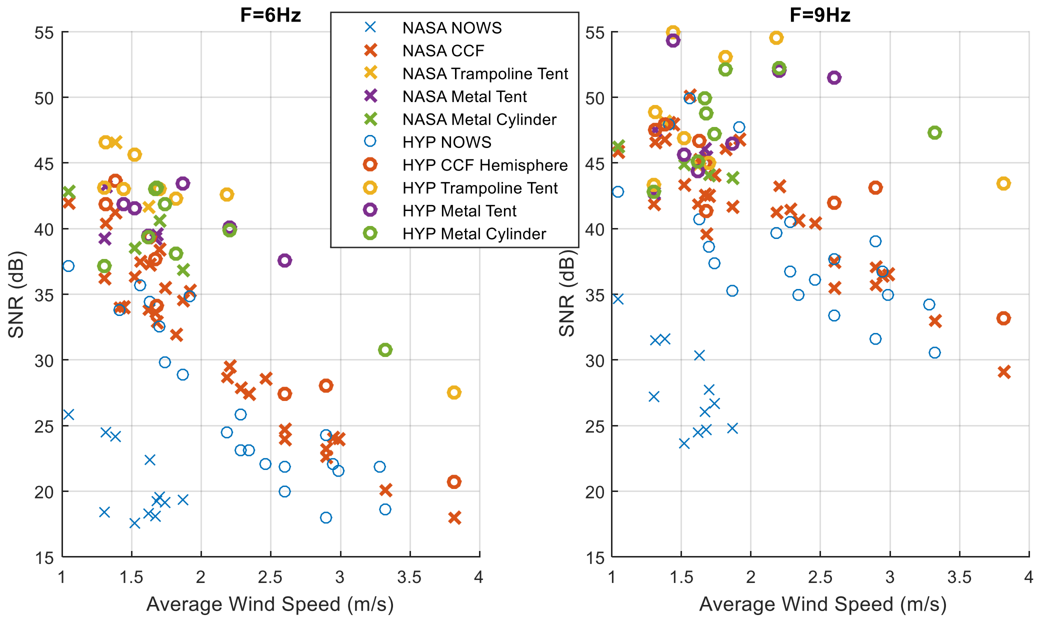

Figure 20. Scatter plot of all field measurements containing 6 and 9 Hz tones for each sensor/windscreen combination. Sensors are indicated by ‘x’ (NASA microphone) or ‘o’ (Hyperion microbarometer); windscreens are indicated by color.

A summary of the results of the SNR analysis is depicted in Figure 21. These results are approximate averages over all test runs, and treat all wind conditions equally. They therefore should be interpreted as overall trends rather than concrete performance specifications. The NOWS cases are shown in tan, closed-cell foam windscreens in blue, other windscreens in green, and the single experiment of a combination windscreen (closed cell foam sphere plus metal cylinder) in yellow. The NASA microphone has no wind mitigation inherently and thus has the worst SNR performance when used without a windscreen; it is therefore used as a lower reference point for improvement obtained by other configurations.

Employing NASA’s closed-cell foam windscreen offered a 16 dB improvement to their microphone. While this is significant when starting from a naked microphone, the Hyperion sensor with its default high-frequency shroud already demonstrates 12 dB better SNR with no additional windscreen. Adding the closed-cell foam hemisphere improved the SNR further by an additional 4-5 dB. The performance of the closed-cell foam box was not ideal due to it not being mounted in the ground and vented as it was designed for, but it still performed reasonably well compared to the other closed-cell foam configurations.

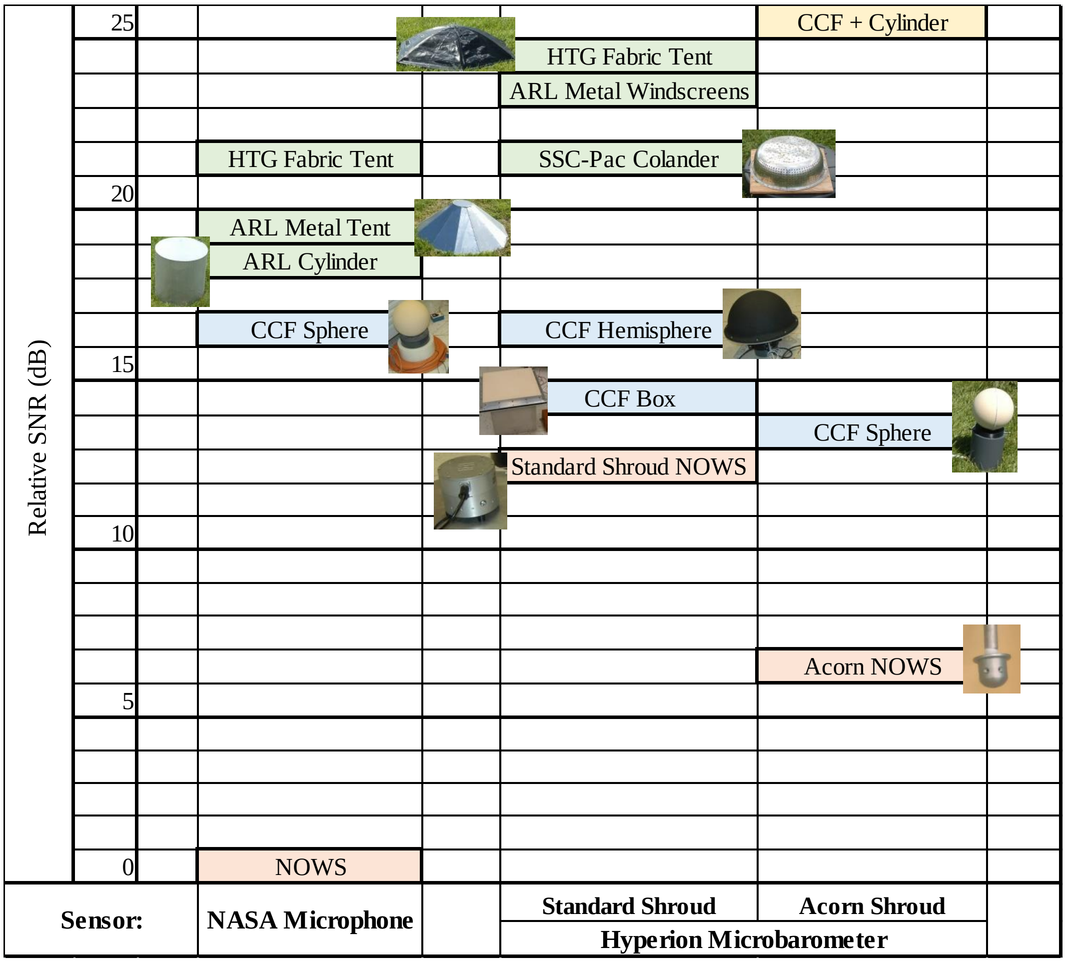

Figure 21. Summary of relative SNR performance for all sensor/windscreen combinations tested. NOWS configurations shown in beige, closed-cell foam in blue, metal and fabric windscreens in green, and combination of closed-cell foam with cylinder in yellow.

The tent and cylinder windscreens showed the best performance of any single windscreen, with the fabric tent showing slightly better wind rejection than the metal designs in some tests. One example of combining a closed-cell foam sphere with the metal cylinder was performed with very good results (the best SNR of any test), but this is only a single data point, and was performed using the less-desirable acorn shroud on the Hyperion sensor. However, this preliminary result indicates that further investigation of combinations of these windscreens should be performed to investigate if it could provide a solution better than either windscreen individually.

4.3.1 NASA Microphone with Various Windscreens

An example of the comparisons between NASA microphone with no windscreen, with CCF windscreens (of 15 and 30 lb. densities), and with other windscreens (tent, cylinder) is shown in Figure 22.

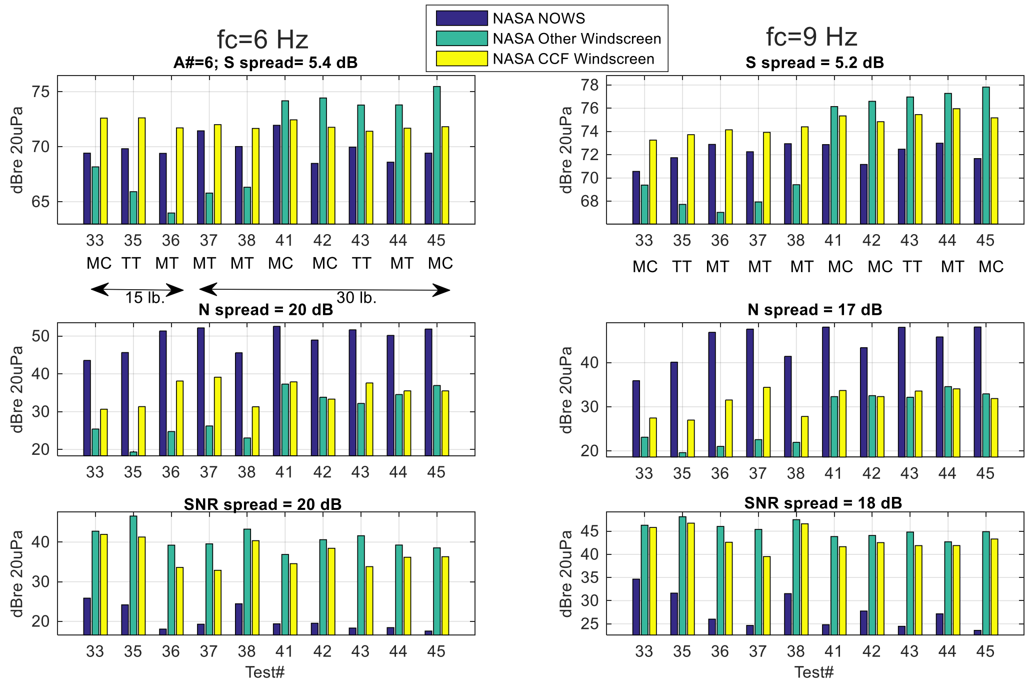

Figure 22. SNR comparison of NASA microphone with no windscreen, closed-cell foam windscreen, and other windscreens: ‘MC’ = Metal Cylinder, ‘MT’ = Metal Tent, ‘TT’ = Trampoline Tent. The CCF windscreen (yellow) used was 15 lb. for 33-36 and 30 lb. for 37–45.

As mentioned earlier, the SNR values are the most trusted metric due to anomalies observed between source and noise levels from test to test. This is evident in Figure 22, where the source levels for tests 33–38 for the “other windscreen” configurations vary significantly, and then suddenly change trend at test 41 and following, at which point they behave more predictably. In looking at the SNR values, a common trend is observed that the NOWS NASA microphone is quite impeded by wind noise. The CCF windscreen performs well at improving the SNR, but any of the other windscreen options do slightly better by 1–5 dB at both 6 Hz and 9 Hz.

4.3.2 NASA Microphone with CCF vs. Hyperion Microbarometer NOWS

The NASA microphone with 18 lb. closed-cell foam windscreen is compared to the Hyperion microbarometer with no windscreen in Figure 23. The highest average wind speed was for Test 51 at 3.32 m/s, and the lowest speeds were Tests 57 and 58 at approximately 1.5 m/s. In all cases the NASA system with windscreen shows an SNR benefit, ranging from 5 dB in Test 47 to only 1 dB in the lower wind cases. There is an apparent gain of 1-2 dB in signal level with reduced noise levels of 1-3 dB.

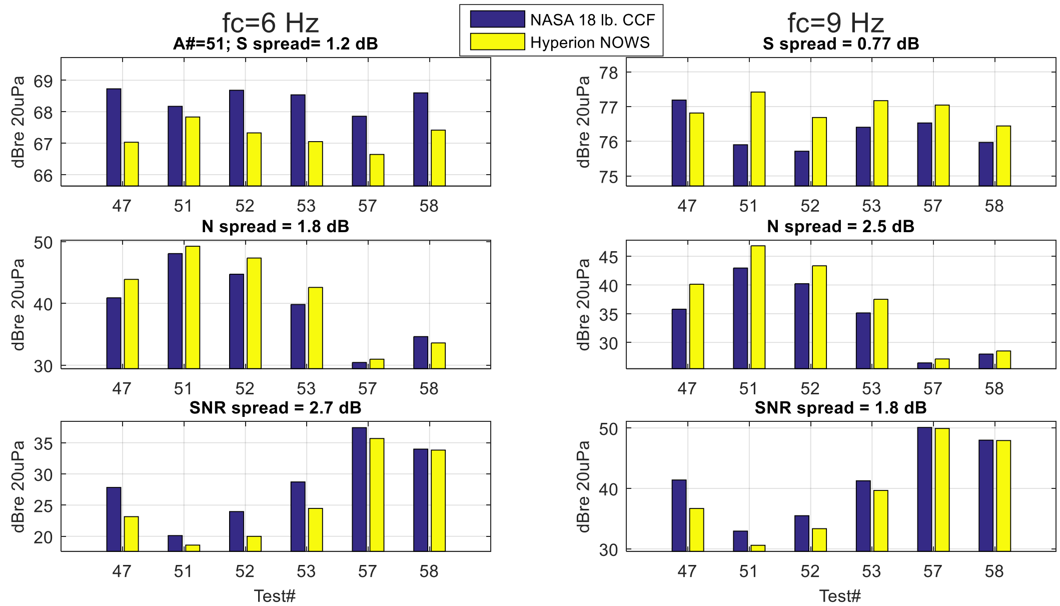

Figure 23. SNR comparison of NASA microphone with 18 lb. closed-cell foam windscreen vs. NOWS Hyperion microbarometer.

4.3.3 Hyperion Microbarometer with Various Windscreens

Several comparisons of the Hyperion microbarometer with no windscreen against various other windscreens are shown:

- Closed-cell foam hemisphere (Figure 24)
- SSC Pacific colander (Figure 25)
- Tent/cylinder windscreens (Figure 26)

In the three comparisons in Figure 24 between the NOWS microbarometer and the CCF hemisphere, a very repeatable 4-5 dB SNR improvement is observed with the closed-cell foam. There is a curiosity in absolute signal and noise level between test case 39 and the later test cases (50 and 60), however, as already mentioned, this is likely a calibration issue with the digitizer and does not affect the SNR results. It is believed that tests 50 and 60 are more correct in terms of absolute levels, which show a 2 dB gain at 6 Hz and 3-4 dB at 9 Hz with the closed cell foam windscreen.

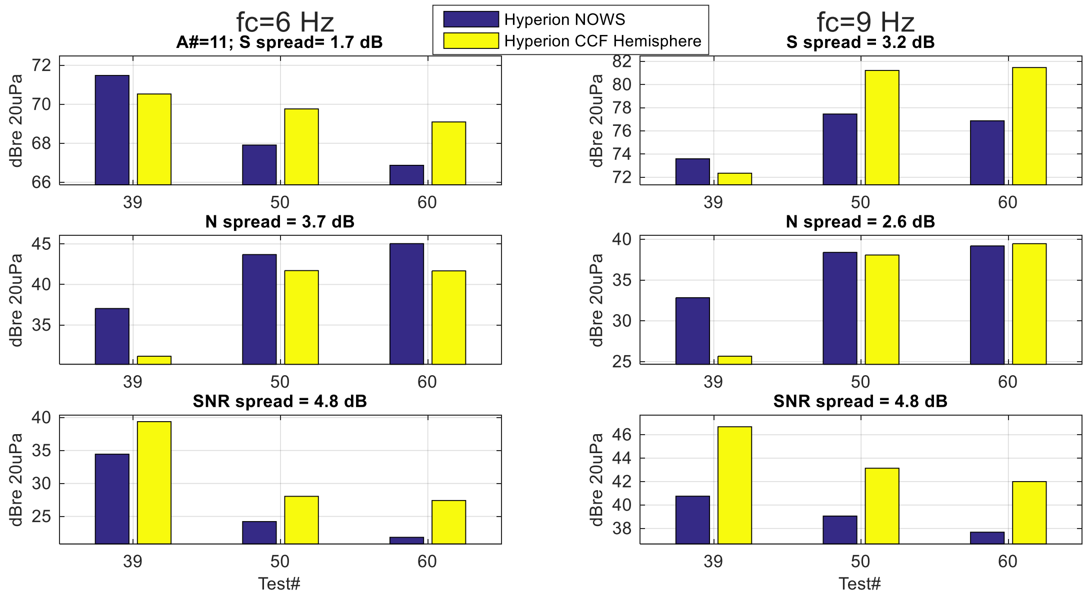

Figure 24. SNR comparison of Hyperion microbarometer with closed-cell foam hemisphere vs. NOWS.

Prior to investing in windscreen development, SSC Pacific had been using an improvised perforated metal windscreen made out of an industrial cooking colander. This windscreen was evaluated in two configurations, with (Test 57) and without (Test 58) felt lining the inside. The case with felt is shown on the left side of Figure 25, with the no felt case shown on the right. Both perform very similarly and provide quite good wind mitigation. Signal-to-noise ratio improvement is approximately 10 dB.

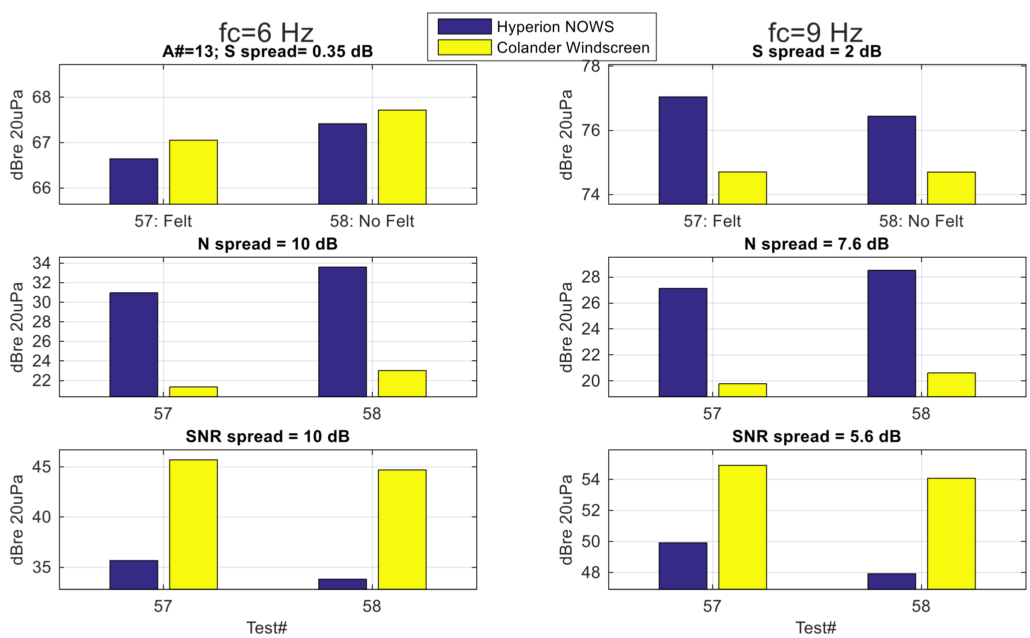

Figure 25. SNR comparison of Hyperion microbarometer with colander windscreen vs. NOWS.

Even greater SNR improvement is observed when using the other ARL and Hyperion windscreens as shown in Figure 26. Most cases show between 10 and 15 dB with as much as 17 dB observed in Tests 52 and 53 using the tent style windscreens.

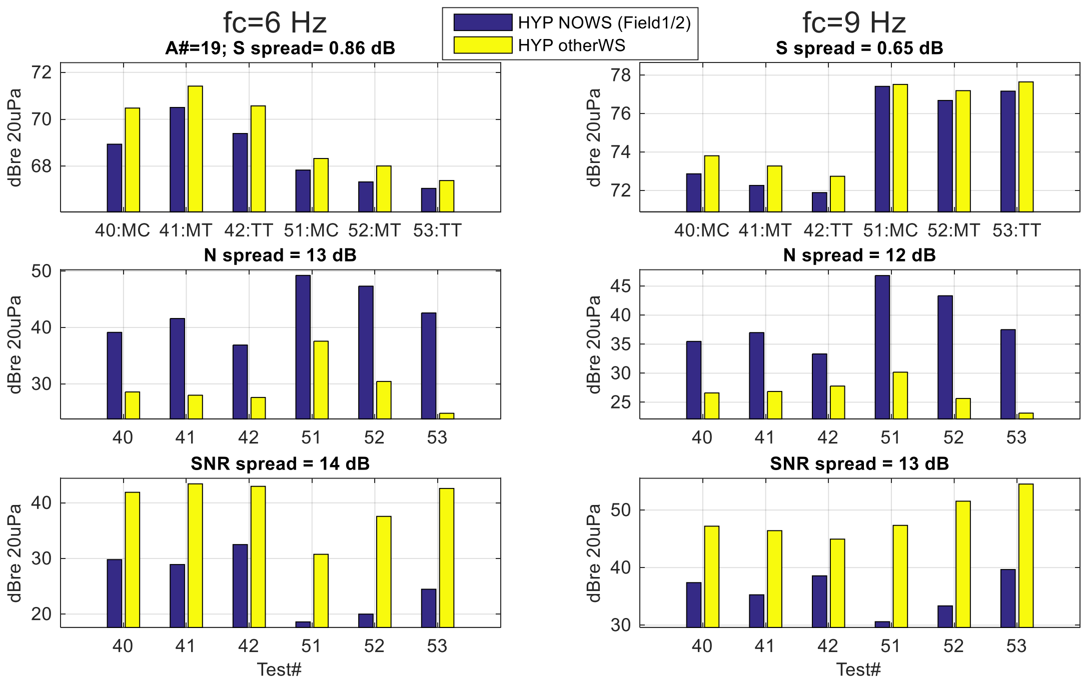

Figure 26. SNR comparison of Hyperion microbarometer with perforated metal and fabric tent windscreens vs. NOWS: ‘MC’ = Metal Cylinder, ‘MT’ = Metal Tent, ‘TT’ = Trampoline Tent.

4.3.4 Hyperion with Acorn Shroud

In this section, we examine the performance of the Hyperion microbarometer with the alternate, acorn shroud. The first two test cases compare the wind susceptibility of the acorn with and without a windscreen. The third test case is unique in that the closed-cell foam sphere windscreen around the acorn was placed inside the cylindrical perforated metal windscreen from ARL, providing nested wind mitigation.

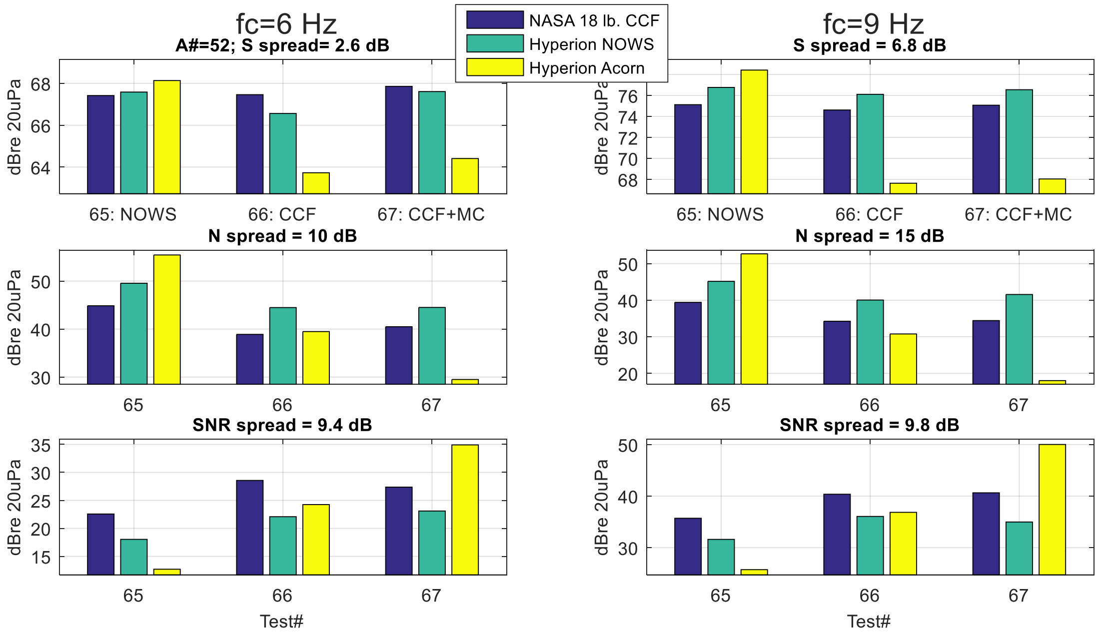

Figure 27. SNR analysis of Hyperion microbarometer with acorn shroud vs. NOWS Hyperion vs. NASA microphone with CCF windscreen. Acorn configurations are: no windscreen (NOWS), closed-cell foam sphere (CCF), and closed-cell foam sphere inside the perforated metal cylinder (CCF+MC).

Based on lab testing with the closed-cell windscreen with the acorn, it did not appear that the back chamber was entirely sealed, as it should have been. Best efforts were made to seal it during the test event, but we think there were still small gaps. In addition, it was not vented due to the fact that these gaps were present anyway. Thus, it is expected that better performance may be possible with a revised implementation of this windscreen and back chamber.

Test 65 in Figure 27 shows that the acorn shroud is more susceptible to wind noise than the standard Hyperion shroud. The addition of the closed-cell foam windscreen improves the performance somewhat, but there is attenuation due to the imperfect back chamber implementation, and the wind rejection is not as good as that obtained with the NASA system. However, adding the perforated metal cylinder outside of the CCF windscreen results in very good SNR performance, 8-9 dB better than the NASA CCF system. As this is only a single data point on a sub-optimal configuration, it may be possible that even greater wind mitigation performance is possible with other combinations, which should be investigated. However, even if the wind mitigation is only as good as the perforated metal windscreen by itself, the extra benefit of water proofing from the closed-cell foam is attractive for our maritime application.

4.3.5 Venting of Closed-Cell Foam Windscreens

A critical design consideration for the closed-cell foam windscreens being developed by NASA is the venting mechanism and back chamber. If the windscreen is not properly vented, reduced transmissivity can occur, resulting in both signal attenuation and reduced SNR.

The testing at NASA was the first use of the hemisphere windscreen and back chamber, and thus some experimentation of venting was performed in order to investigate what performance could be achieved with different configurations. The first set of comparisons, shown in Figure 28, were performed in the controlled lab environment and focused on the attenuation of source tones. The non-vented configuration (Test 11) is prior to drilling a venting hole through the aluminum mounting plate, and thus the interior volume of the windscreen was completely sealed. As expected, this results in severe attenuation of the source signal by about 14 dB; however, there is equivalent attenuation of the noise such that the SNR obtained is the same as for the NOWS sensor.

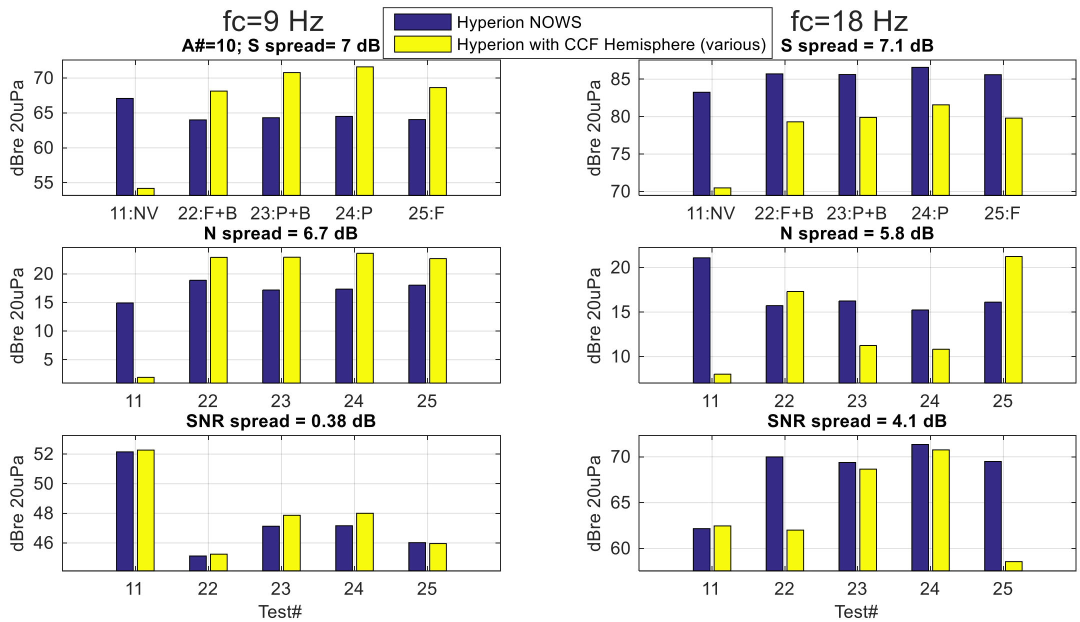

Figure 28. Comparison of different venting and back chamber configurations for the Hyperion sensor with CCF hemisphere windscreen in the lab. Test configurations: “NV” = no vent, “F” = foam, “B” = bubble wrap, “P” = popsicle stick

We then vented the system by drilling a hole through the aluminum plate into the back chamber. Testing revealed similar performance to the unvented case, so further investigation was performed, involving packing the windscreen with bubble wrap in order to decrease the air volume inside. Unfortunately, the data was lost for these tests, but recorded notes document that minimal changes were observed.

The next theory, which proved correct, was that the back chamber was sealed to the floor, rendering the venting ineffective. The second configuration shown in Figure 28 (Test 22) is for the back chamber, with bubble wrap still inside the windscreen, placed up on an open-cell foam pad approximately 1 inch thick. This does in fact allow the back chamber to vent and rather than signal attenuation, a gain of 3-4 dB is observed compared to the NOWS microbarometer at 9 Hz (top left plot); background noise is similarly increased (middle left plot), once again producing equivalent SNR at 9 Hz. (bottom left plot). At 18 Hz, attenuation of 6 dB is observed due to the low-pass nature of the closed cell foam (top right plot); however, the noise is not attenuated (middle right plot), resulting in an 8 dB lower SNR value (lower right plot). This indicates that noise is able to enter the system by a different means (through the open-cell foam) than the signal, which passes through the closed-cell foam windscreen, or that the foam induces additional noise to the sensor, possibly via vibration.

A second method of breaking the seal of the back chamber to the floor is then shown, removing the foam pad and instead placing a popsicle stick under one edge of the back chamber to provide a small air gap (Test 23). A slight additional gain is observed, corresponding to a 1 dB SNR improvement at 9 Hz. At 18 Hz, the noise level is significantly reduced for this configuration compared to Test 22, resulting in improved SNR. Thus, the path for higher frequency background noise to enter the sensor is greatly reduced with the small gap created by the popsicle stick compared to the foam pad.

It was theorized that the venting of the bottom of the back chamber was the only factor impacting performance, and not the bubble wrap inside. Thus, the bubble wrap was removed and the tests were repeated, yielding similar results (Tests 24 and 25 for popsicle stick and open-cell foam pad, respectively) and confirming this hypothesis correct. Note that the same SNR patterns at 18 Hz for the foam pad (poor SNR) vs. popsicle stick (good SNR) remain true (bottom right plot).

Power spectra and difference spectra are shown in Figure 29 for the test cases just analyzed in Figure 28. The power spectra on the left shows that the attenuation that results from no venting at all gradually decreases with lower frequency until the two responses are nearly identical below 0.1 Hz. The other cases with proper venting all show less than 1 dB difference with the reference sensor below 4 Hz. There is a gain observed from 4 Hz to 15 Hz that is similar to all configurations. However, there is an additional gain peak at 20 Hz that is only present when the back chamber is on the foam pad (Tests 22 and 25). The foam pad also shows attenuation that continues up through 100 Hz, whereas the popsicle stick vent responses return to 0 dB difference by 80-100 Hz. This indicates that transmissivity is more affected in the higher frequency band by the method of venting than the lower frequency band. However, as will be shown in the next analysis (Figure 32), wind mitigation is affected in the lower frequency band down to at least 0.2 Hz by different venting designs.

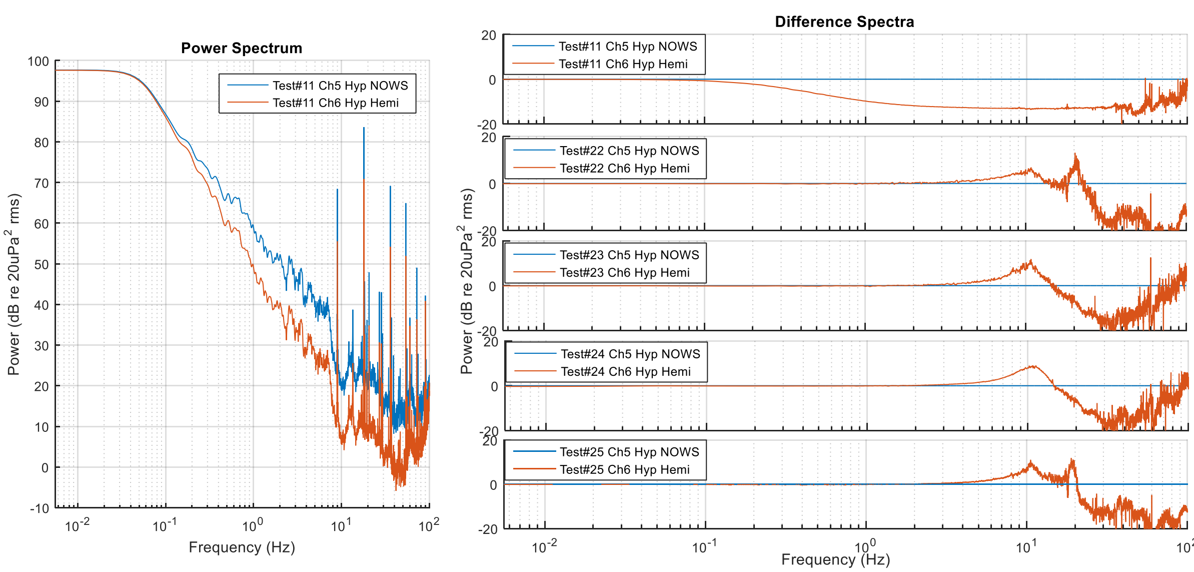

Figure 29. Power spectra of non-vented CCF hemisphere vs. NOWS microbarometer (left) and difference spectra of various configurations of hemisphere back chamber vs. NOWS microbarometer (right).

Another comparison of venting was performed in the field. This involved different configurations than were examined in the lab, with the intention of exploring what might work for deployment on a USV; pictures of them are shown in Figure 30.

Figure 30. Different venting configurations evaluated in the field: Test 61 in tray of water (left), Test 62 in tray of water with air gap (center), and Test 63 spaced off ground on wood blocks (right).

The first test shown in Figure 31 (Test 60) is for the “standard” vent, placing the back chamber directly on the ground and using the ground as a large pressure release volume that is isolated from the atmosphere. This case shows the 5 dB SNR improvement described in Section 4.3.3 for the Hyperion sensor with CCF windscreen (green series).

The next configuration (Test 61) placed the back chamber in a shallow pool of water (left picture in Figure 30) to identify whether the water enabled sufficient pressure release or not. The results are similar to the non-vented case (Test 64), indicating that the bottom of the back chamber actually sealed tightly enough to the bottom of the tray that the water was inconsequential. Note that with the presence of background wind noise in Tests 61 and 64, contrary to Test 11 in the lab, there is an SNR loss when the back chamber is not properly vented due to the signal being attenuated more than the noise.

The next test (62) included a small piece of plastic under one edge of the back chamber to avoid sealing it against the bottom of the tray, similar to the popsicle stick used in Tests 23 and 24 in the lab, but here the water in the tray still enclosed the bottom of the back chamber. This reduced the signal attenuation by about 50%, while restoring the background noise level to the same as without a windscreen, resulting in poor SNR performance. Thus, it does not seem that using water as a pressure release volume is promising, although it is possible that different configurations (deeper water, etc.) could provide different results.

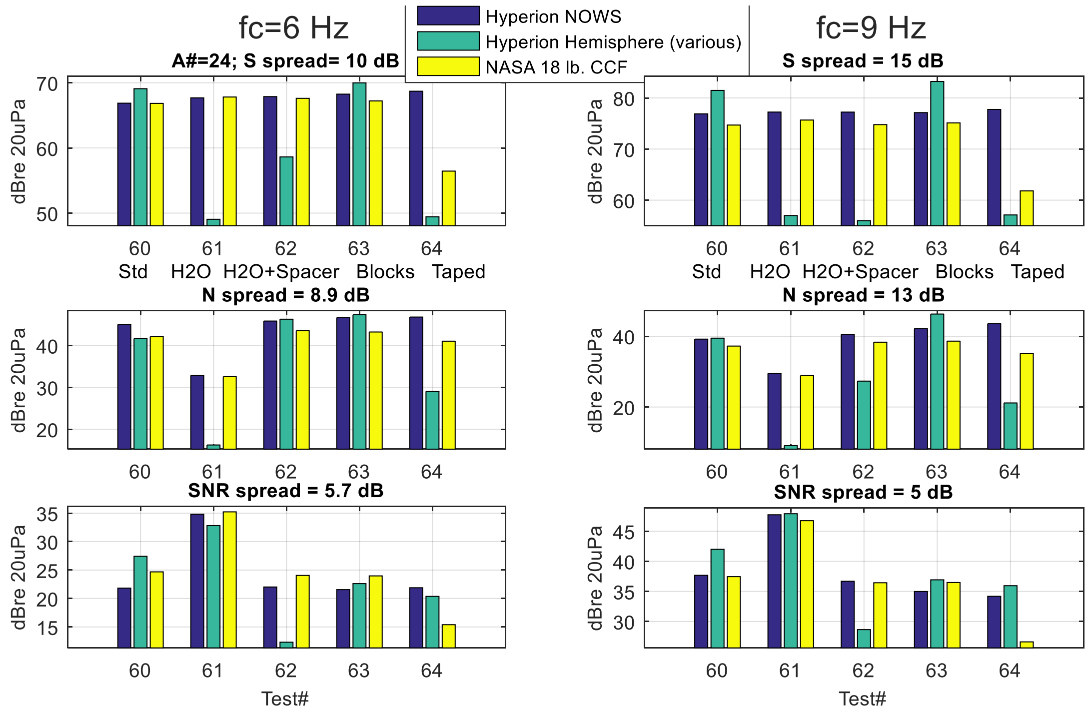

Figure 31. Comparison of different venting configurations for the Hyperion sensor with closed-cell hemisphere windscreen in the field. Legend for test cases: “Std” = standard venting to ground, “H2O” = venting to water bath, “H2O+Spacer” = water bath with spacer, “Blocks” = spacing the entire assembly off the ground on blocks, “Taped” = taping over the vent hole (non-vented case).

A third configuration (Test 63) was to test the performance when allowing the back chamber to vent to the atmosphere by spacing the system up on wood blocks (center picture in Figure 30). As expected, this results in zero wind mitigation and similar SNR performance to the NOWS sensor. The conclusion of this analysis is that simple alternatives to using ground is not effective and a more complex back chamber needs to be designed in order to achieve good performance when ground is not available, such as on a maritime platform.

The third sensor included in the analysis shown in Figure 31 is a NASA microphone CCF windscreen (yellow series). For Tests 60-63, this sensor was vented normally, with the back chamber sitting on the ground. For Test 64, the venting hole was taped over to eliminate any venting. As seen in the lower two plots, the SNR performance for Tests 60-63 is slightly better than the NOWS Hyperion sensor. However, once the vent was taped over, the signal is attenuated more than the noise and there is a 6-7 dB SNR reduction. Thus, again, an improperly vented back chamber can result in more signal attenuation than noise in the presence of wind, imposing not only an overall attenuation, but poorer signal detection performance.

The power spectra for the outdoor tests are shown in Figure 32. The curves for the standard vent and non-vented windscreens are both shown for reference. The water vent (Test 62) clearly has a negative effect on the wind/background noise mitigation from around 1 Hz to 6 Hz. The effect of putting the back chamber up on blocks is seen more from 3 Hz to 15 Hz.

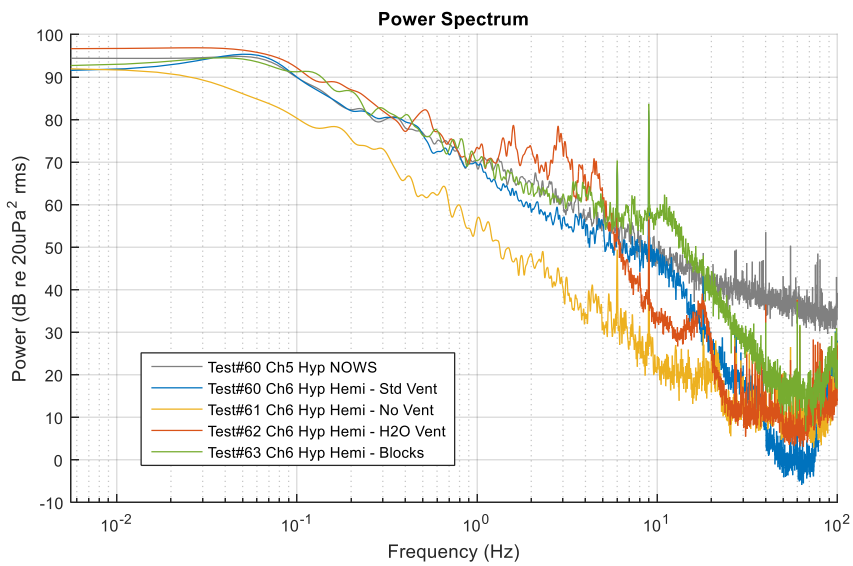

Figure 32. Power spectra for outdoor hemisphere venting comparison: no windscreen, standard vent to ground, no vent (sealed), vent to water, and suspended on blocks.

4.4 SPECTRAL ANALYSIS

In addition to the analysis at the specific tones of the source, which enable calculation of signal-to-noise ratio, broadband analysis was also performed using power spectra.

4.4.1 Broadband Wind Mitigation

Tests 28 and 29 were performed outside, with no source active; they had average wind speeds of 1.53 and 1.20 m/s, respectively. The difference spectra shown in Figure 33 compare a NASA microphone with closed-cell foam windscreen to one without any windscreen. It is evident that the 14 dB wind noise attenuation reported in Figure 21 is relatively consistent across the entire infrasound band, with fluctuations of approximately ±5 dB until 30 Hz at which point the attenuation of the foam dominates. It should be recognized that this comparison assumes all infrasound content is background noise and does not account for any infrasound signals that may be present in the ambient environment, and is therefore only a rough estimate that the SNR improvement observed at 6 and 9 Hz is somewhat representative of what would be observed at lower frequencies. It is recommended that further testing, with a source that can be used at lower frequencies, be performed to verify this conclusion.

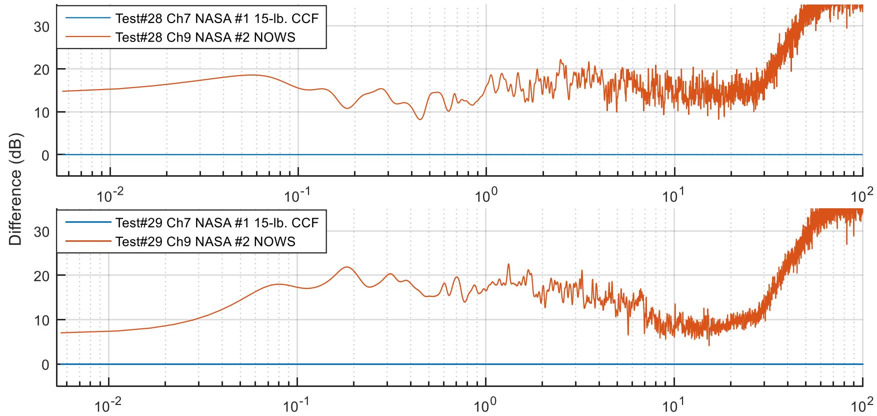

Figure 33. Difference spectra of NASA microphone with and without a windscreen for test 28 (Top) and Test 29 (bottom)

A comparison of the Hyperion microbarometer with the closed-cell foam hemisphere windscreen and with various other windscreens is shown in Figure 34. The hemisphere attenuates wind noise better than the foam box across most of the frequency band. However, both the metal cylinder and the trampoline tent windscreen demonstrate better wind mitigation than the hemisphere until 10 Hz. Above 10 Hz it is not clear whether the reduced levels observed with the hemisphere are wind noise rejection, or overall attenuation due to the frequency response of the foam without a source tone to compare, but it is assumed to be overall attenuation. The cylinder may do slightly better than the trampoline tent at lower frequencies (less than 0.4 Hz).

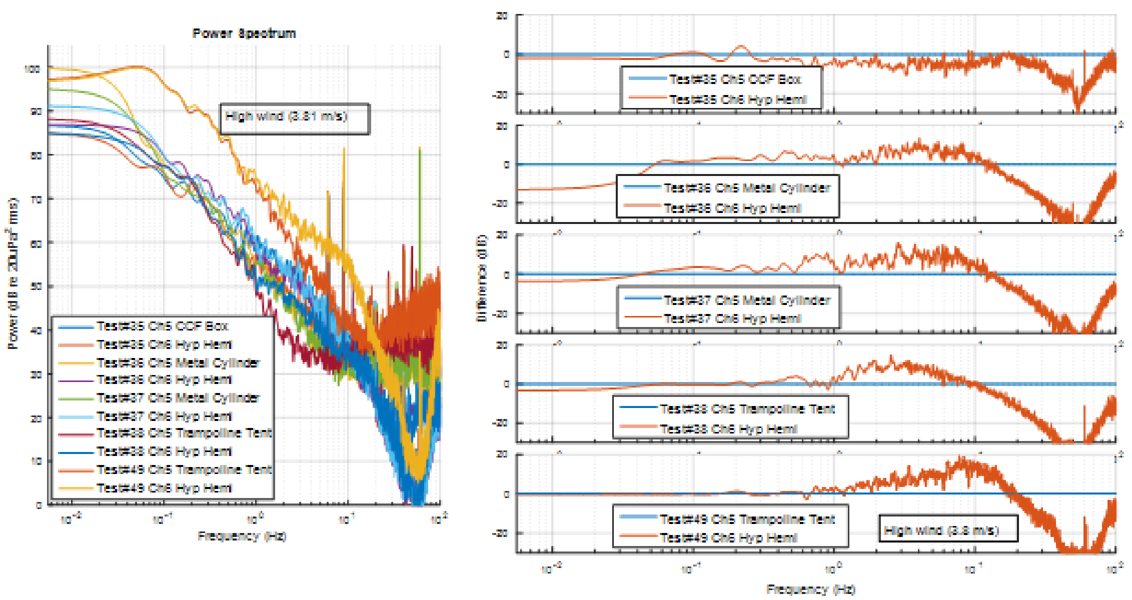

Figure 34. Spectra of Hyperion microbarometer with closed-cell foam hemisphere compared to other windscreens (left) and difference spectra between hemisphere and other windscreens for each test (right): closed-cell foam box (right, 1st), metal cylinder (right, 2nd and 3rd), trampoline tent (right, 4th and 5th)

The last test shown, #49, was the highest average wind observed of all tests performed with an average speed of 3.81 m/s. From the spectra on the left, it is apparent that this wind velocity produces wind noise that is up to 15 dB higher than the lower wind cases for a large portion of the infrasound band down to 0.03 Hz. The trampoline tent blocks higher frequency wind noise (1–10 Hz) up to 15 dB better than the hemisphere, particularly near 10 Hz. However, the two windscreens are similarly ineffective at mitigating very low frequency wind noise below 1 Hz.

Similar comparisons of the NASA sensor with 15 and 30 lb. closed-cell foam windscreens to other windscreens (metal cylinder, trampoline tent, and metal tent) are shown in Figure 35 and Figure 36, respectively. In Figure 35, the other windscreens all appear to reject more background noise from about 0.07 Hz to 15 Hz. However, based on other analysis of these test numbers, we think there is a bias issue for some of the channels that seems to fluctuate from test to test. Our test notes do not capture why these changes should occur, and thus absolute levels between channels are questionable. However, based on other analysis as well, we do not believe there is significant, if any, attenuation at the source tone of 6 Hz from any of the windscreens. The relative levels of the source tone at 6 Hz, called out in the data markers, are 5–7 dB lower for the other windscreens, indicating that there is a calibration issue of approximately this amount for these tests. Accounting for this, the difference between the NASA windscreen and others is reduced; the tent windscreens still block background noise from 1 Hz to 10 Hz more effectively than the NASA closed-cell foam, but the cylinder only does better from 5 to 10 Hz. From 0.05 to 1 Hz the tent windscreens do slightly better than the CCF, while the cylinder is comparable or slightly worse than the CCF.

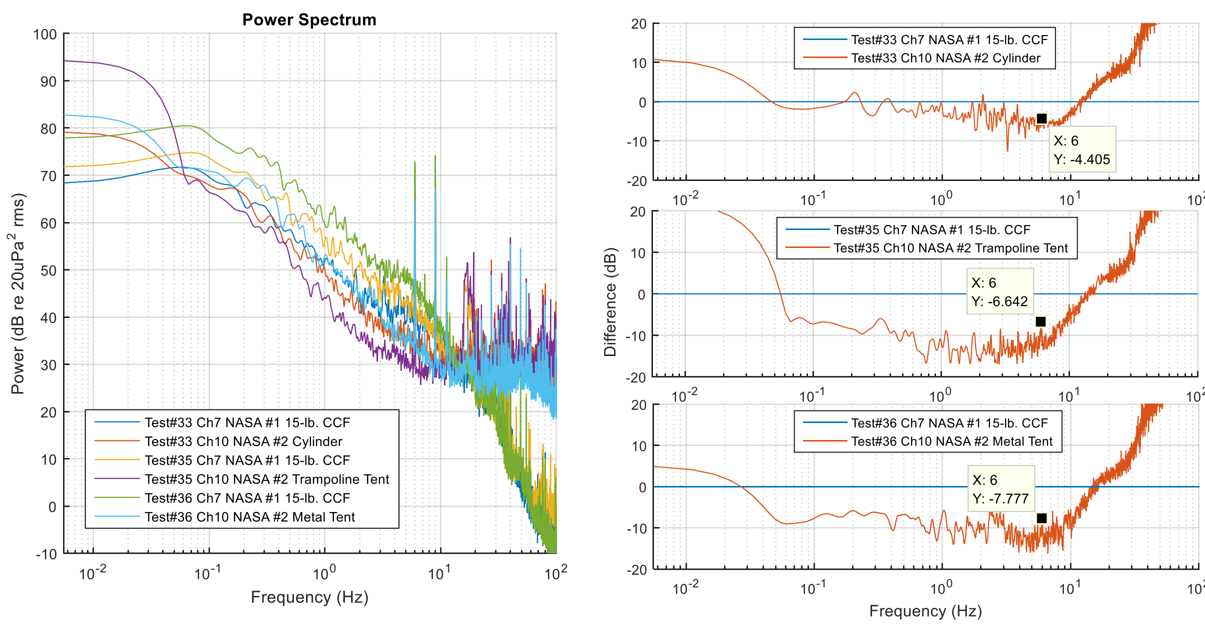

Figure 35. Comparison of NASA 15 lb. closed-cell foam windscreen to other windscreens

The tests with the 30 lb. closed-cell foam happen later, and it appears that calibration is better and more stable. Similar results to the 15 lb. case are obtained, with the tent windscreens performing slightly better than the CCF from 1 to 10 Hz. The cylinder does not mitigate wind noise as well below about 5 Hz, and the tents are approximately equivalent to the CCF below 1 Hz, until 0.06 Hz at which point the closed-cell foam blocks noise much more.

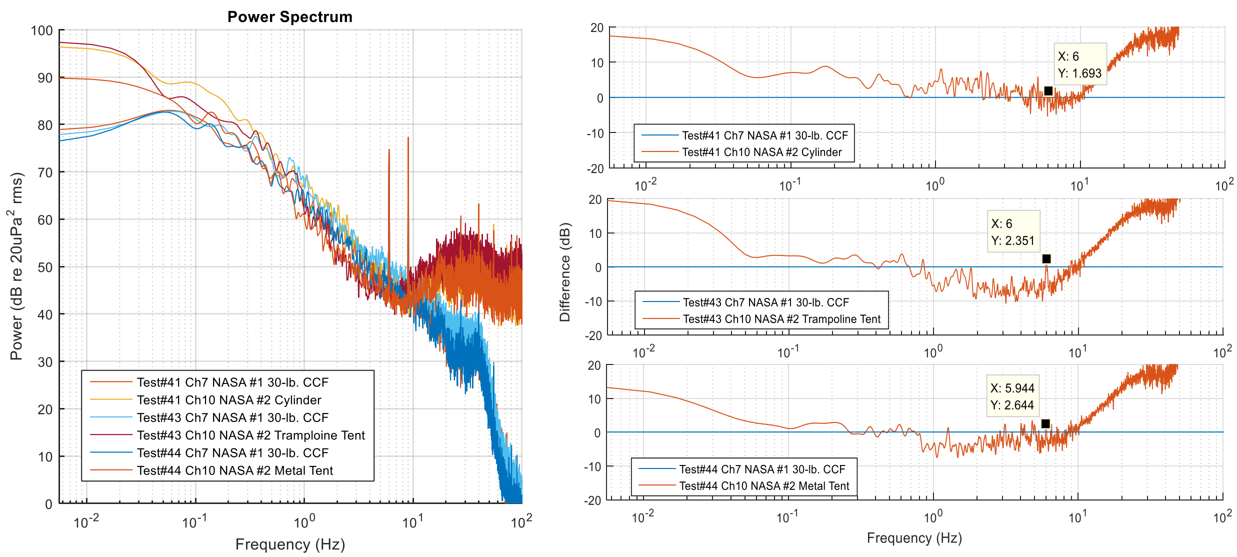

Figure 36. Comparison of NASA 30 lb. closed-cell foam windscreen to other windscreens

4.4.2 Transmissivity Using Source Sweeps

In order to evaluate the transmissivity of the windscreens over as broad a band of infrasound frequencies as possible given the capabilities of the sources used, linear frequency sweeps were performed in the lab, with frequency starting at 7 Hz and increasing to 20 Hz, as shown in Figure 37. It is observed that all four sensor configurations follow the same amplitude fluctuations, indicating that this is due to the non-flat frequency response of the infrasound source. The Hyperion with hemisphere windscreen is significantly attenuated (~12 dB) due to not yet being properly vented at the time of this test (as discussed in Section 4.3.5). Also, the NOWS Hyperion is slightly below the level of the NASA sensors due to mis-calibration in the DAQ which was resolved in later tests. With these factors in mind, the responses of all sensors agree closely at the starting point of 7 Hz. The NASA NOWS and Hyperion NOWS configurations continue to match closely over the entire frequency band. The NASA CCF configuration starts off just 1 dB attenuated at 7 Hz and remains nearly agreeing with the NOWS sensor until about 10 Hz. From 10 Hz to 20 Hz attenuation gradually increases to nearly 10 dB due to the low-pass nature of the closed-cell foam.

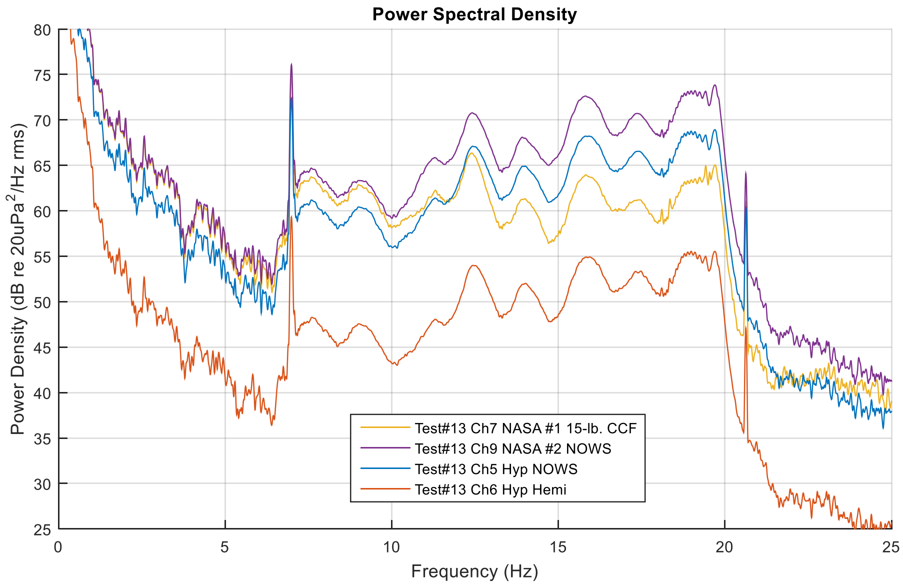

Figure 37. Power spectral densities for NASA and Hyperion sensors both with and without closed-cell foam windscreens for linear frequency sweep (Test 13)

Figure 38 shows the difference spectra to demonstrate the attenuations of each windscreen clearer. The NASA NOWS configuration was used as a reference for the NASA CCF windscreen, and likewise, the NOWS Hyperion was used as a reference for the Hyperion with CCF hemisphere. As discussed, the roll-off of the closed-cell foam is clearly seen beginning most notably at 10 Hz. Interestingly, there is a region of reduced, yet highly variable attenuation from 22-30 Hz, followed by steep attenuation above this. As there is no source tone above 20 Hz, it could be rather that there is background noise coupling into the back chamber rather than passing through the windscreen.

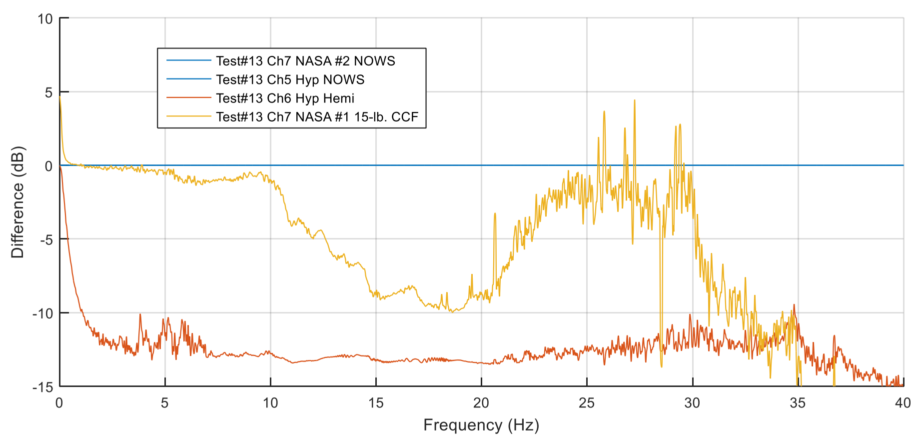

Figure 38. Difference power spectral densities for NASA and Hyperion sensors both with and without closed-cell foam windscreens for linear frequency sweep (Test 13)

4.4.3 Jet vs. Wind Noise

During a number of our test runs, several jets took off from Langley Air Force Base, approximately one mile as the crow flies from our test location. The analysis shown in Figure 39 attempts to identify acoustic frequencies detected from jets and compare these to the wind noise spectra observed. The left-hand plot show several cases with lower wind; the right-hand plot shows several cases with higher wind, using one curve from the low wind as a baseline (shown bold-dashed). All series are 60 seconds of data; for those with jets present, numerous jets took off in succession such that they spanned all, or most, of the 60-second segment. The average wind speed over each 60-second segment was computed and is labeled in the legend for each curve.

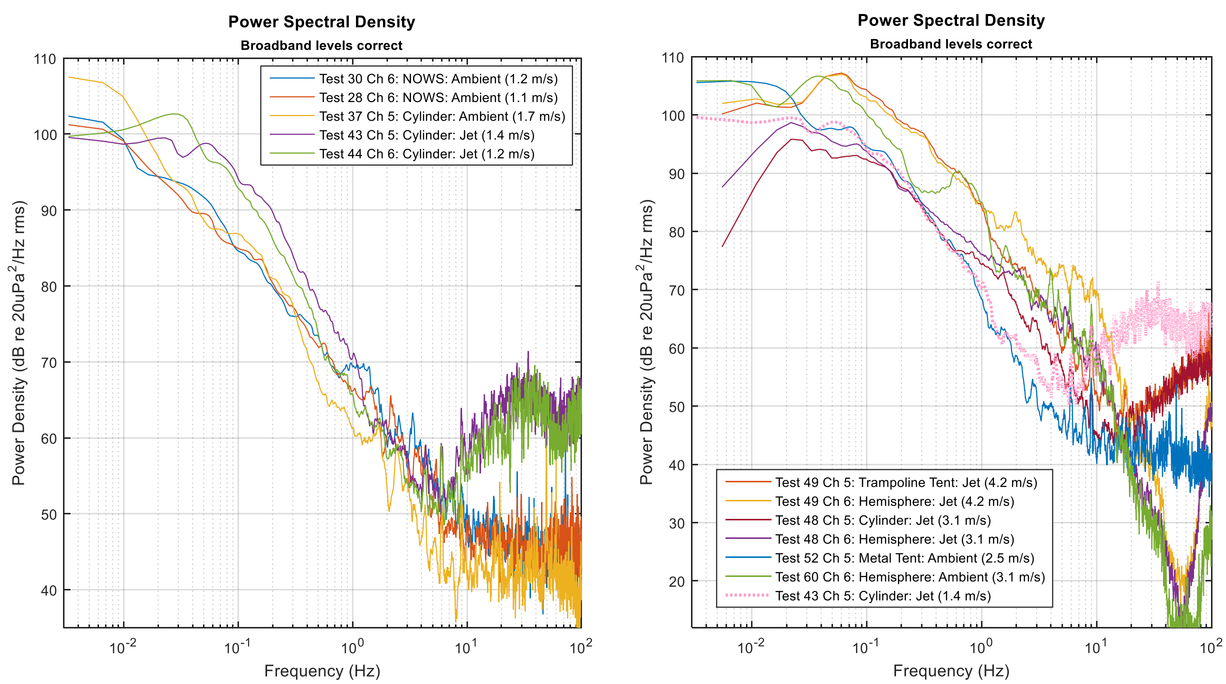

Figure 39. Power spectral densities of test examples comparing segments of jet take-offs with ambient; low wind cases (left) and higher wind cases (right).

The low wind cases on the left more clearly indicate jet noise due to the lower background noise. The green and purple curves are two different tests with jets present, while the other curves are ambient with no jets present. The two jet curves are fairly consistent with each other in overall shape, demonstrating an excess of 5-10 dB all the way from 0.02 Hz to almost 1 Hz above the ambient cases. In addition, there is clearly jet noise present starting at about 5 Hz and extending up into the audible range. It is inferred that this is indeed jet noise due to the fact that the yellow ambient curve is with the same windscreen as both of the jet curves and even has a higher average wind speed, yet the spectral level is lower. The other two ambient cases are without a windscreen, albeit at slightly lower average winds, yet still show lower spectral levels as well.

The higher wind cases are more ambiguous to glean conclusions from. It is inferred that most of these data series are wind noise limited. The Test 43 curve (bold-dashed) from the low wind cases is included as a reference point. The two curves from Test 48 with jets present are close to, but slightly lower than the curve from Test 43 from 0.02 Hz to 0.3 Hz, at which point the trend flips and the wind noise clearly dominates above any jet noise that may be present until about 20 Hz. It is possible that these levels are jet noise and that the jets provided a lower amplitude signal due to being different aircraft, there being different wind direction, or other factors, as the higher frequency content is significantly different as well (15 dB lower amplitude from 10 to 40 Hz). However, it is curious that the same windscreen (closed-cell foam hemisphere) yields a higher response across the entire infrasound band for the ambient case at equal mean wind speed (green curve). Clearly, the higher wind cases (Test 49, red and yellow) are wind noise limited across the entire infrasound band and only the jet noise above 20 Hz is observable.

Overall conclusions from this brief analysis is that there is likely infrasound observed from jet take-offs from 0.02 Hz to 1 Hz, and 5 Hz and higher. The amplitude is observable above low wind, but the windscreens tested here may not provide sufficient wind noise to observe the jet noise at higher wind speeds in the infrasound band.

5. CONCLUSIONS

The primary purpose of this test event was to investigate the performance of various infrasound windscreens that could possibly be used on an unmanned surface vehicle. In particular, it was desired to investigate whether the closed-cell foam windscreens being developed by NASA are indeed able to mitigate wind noise without attenuating the source signal, due to their basis on a different physical mechanism. In addition, the NASA infrasonic microphones were evaluated against the Hyperion microbarometer as two different sensors which could be considered for such an application.

The actual sensor performance was evaluated in terms of both frequency response and wind sensitivity when no windscreen is used. The two sensors performed very similarly in lab testing with no wind present and this test provided a good validation of the flat responses of both over most of the infrasound band. However, the NASA microphone is much more susceptible to wind noise with no windscreen than the Hyperion microbarometer due to the fact that the Hyperion sensor has a perforated shroud built into it.

The closed-cell foam windscreens were evaluated in terms of both wind mitigation as well as signal transmissivity. It was confirmed that a properly designed and vented back chamber is crucial to optimal operation of the CCF windscreen. With such a chamber, the windscreens showed less than 2 dB of attenuation over most of the infrasound band, but significant attenuation above this (greater than 10 Hz) due to the low-pass nature of the foam; this cutoff frequency can be controlled by changing the density of the foam used. Wind noise rejection was significant, but not the best of the windscreens tested. It was confirmed that a hemispherical closed-cell foam windscreen and back chamber were successfully developed for the Hyperion microbarometer that is comparable in wind noise rejection to the CCF spheres developed by NASA for their microphone system.

Improper venting of the CCF windscreen will result in significant attenuation of both signal and wind noise, on the order of 15 dB. In an environment with no wind noise, equivalent SNR may be obtained, but in the presence of wind, the background noise is not attenuated to the same degree as the signal, resulting in an overall loss in SNR.

The compact perforated metal and fabric windscreens tested did not demonstrate any signal attenuation, and performed very well in terms of wind noise mitigation in the frequency bands investigated, with SNR improvements of 5–8 dB better than what was achieved with the closed-cell foam windscreens (Figure 21). Although the wind mitigation of the CCF windscreens may not be quite as high as other options, they are still attractive for our maritime application due to their water proofing properties. In addition, they are more compact than the tent and cylinder windscreens tested, making them more suitable to deployment on small USVs. These results warrant further investigation of CCF windscreen implementations for our application.

5.1 LESSONS LEARNED

Some lessons learned through this experiment are:

- Reference sensor: It would have been beneficial to always have a reference sensor with no windscreen to identify anomalies in the environment, source levels, etc.
- Calibration: While we performed an initial sensor analysis in the lab without windscreens, which identified some calibration errors, this was not repeated again. This should have been repeated when we moved the equipment from the lab to the field to verify everything was set up identically. It would have also been useful to check calibration levels

periodically (all sensors without windscreens) to identify any anomalies as early as possible.

5.2 FUTURE STEPS

While the testing presented in this report was performed to as complete a degree as possible given the time and assets available, there are several gaps that could be investigated in future tests.

First, the wind speeds encountered during this test were mostly lower, with some moderate winds on the later tests. There were no extremely high winds. As expected, the results shown (Figure 20 in particular) indicate reduced wind mitigation, and therefore reduced SNR, with increased wind velocity. However, there are many more low wind data points than higher wind data points from which our conclusions are drawn. A test involving higher air speeds (either natural wind, or artificially generated) would be valuable to compare the performance of the different windscreens in these cases. It is possible that trends may be different at some wind speeds than what are shown in this report.

Similarly, the infrasound sources available for this test were only capable of producing tones from 6 Hz and above. This is the upper range of the infrasound band and many events of interest produce frequencies significantly lower than this. While inferences were made in this report to performance based on ambient noise measurements, more precise calculations using known sources at lower frequencies would be valuable to more definitively characterize windscreen performance in the lower region of the infrasound band.

It would be of interest to further investigate combinations of the windscreens evaluated individually during this test. There was only one test event (Test 67) which involved a closed-cell foam sphere nested inside a perforated metal windscreen. It is possible that combinations of these windscreens may provide a capability that is better than any single one by itself. It may be required to modify shapes and sizes in order for this testing to be performed.

As mentioned, a properly designed back chamber is crucial to the performance of the closed-cell foam windscreens. The current back chamber design relies on using the ground as a large pressure equalization volume. In order for a system like this to be deployed on a USV, a different back chamber would need to be developed that would not require ground in this way. The development of such a back chamber is being pursued by SSC Pacific in collaboration with NASA.

While the wind mitigation properties of the closed-cell foam were investigated in this test, it did not evaluate the water mitigation aspect. Some preliminary tests have been done with the foam to verify its waterproof properties, but more extensive testing needs to be done of a complete, assembled system to validate that it can be made waterproof to at-sea conditions. This will be performed once the modified back chamber just mentioned is designed and constructed. In addition, long duration testing will need to be performed to validate the longevity of the foam when exposed to sunlight and salt water for extended periods (several months).

REFERENCES

1. Zuckerwar, A. J. 2010. “Theory of compact nonporous windscreens for infrasonic measurements,” 127 (6), June 2010, p. 3327–3334
2. Shams Q. A., A. J Zuckerwar, and B. S. Sealey. 2005. “Compact nonporous windscreen for infrasonic measurements , *Journal of the Acoustical Society of America*,” 118 (3), p. 1335–1340.
3. Shams Q. A., C. G. Burkett, A. J. Zuckerware, C. C. Lawrenson, and M. Masterman. 2008 “A Portable Infrasonic Detection System,” *NASA Technical Report.*
4. Alberts, W.C., S. Kirkpatrick; S. M. Tenney; and .J M. Noble.. 2013. “Assessment of Operational Progress of NASA Langley Developed Windshield and Microphone for Infrasound,” Army Research Laboratory Technical Report
5. Nicolas D.; H. Maxime; D. Stéphane. 2016 “Effectiveness of Nonporous Windscreens for Infrasonic Measurements,” *Journal of the Acoustical Society of America*,” 139 (6), June 2016, p. 3177–3181
6. On-line web article, Hyperion Technology Group Incorporated, “Infrasound Sensors.” Available online at: http://hyperiontg.com/expertise/infrasound-sensor/. Accessed October 23, 2019.

This page is intentionally blank.

APPENDIX A
ADDITIONAL DATA

A.1 OVERVIEW

A comparison summary table is detailed in Appendix A. The table contains a row for each sensor configuration tested (sensor, windscreen, and configuration). The subsequent columns contain average performance for each configuration regarding wind reduction and SNR improvement for low wind cases and high winds cases. Note that these values are very rough approximations gleaned from a relatively few number of data samples and should not be taken as absolute performance specifications. The table is intended to convey overall performance trends as observed from this specific test event.

A.2. COMPARISON SUMMARY TABLE

Sensor	Windscreen	Configuration	Transmissivity	Low Wind		High Wind	
				Wind Reduction	SNR Improvement	Wind Reduction	SNR Improvement
NASA Microphone	NASA CCF	15 lb. Sphere	2 dB loss at 9 Hz; 7 dB loss at 18 Hz (lab) 2 dB gain at 6 Hz and 9 Hz (field)	13 dB vs. NASA NOWS at both 6 Hz and 9 Hz 2-3 dB vs Hyp NOWS	15 dB vs. NASA NOWS 4-5 dB vs. Hyp NOWS		
		18 lb. Sphere	2 dB gain at 6 Hz; 0 dB gain at 9 Hz (field)	2-3 dB vs. Hyp NOWS	2-5 dB vs. Hyp NOWS	1-2 dB vs. Hyp NOWS	2-3 dB vs. Hyp NOWS
		30 lb. Sphere	2 dB gain at 6 Hz and 9 Hz (field)	14 dB vs. NASA NOWS at both 6 Hz and 9 Hz 2-3 dB vs. Hyp NOWS	16 dB vs. NASA NOWS 5 dB vs. Hyp NOWS		
		Box	6 dB loss at 9 Hz 11 dB loss at 18 Hz				
	Other WS	Hyp Trampoline Tent	Levels too confusing to assertain		21-22 dB vs. NASA NOWS		
		ARL Metal Tent			19-20 dB vs. NASA NOWS		
		ARL Metal Cylinder			17-18 dB vs. NASA NOWS		
Hyperion Microbarometer	CCF	SSC-Pac Hemisphere	5 dB gain at 9 Hz; 6 dB loss at 18 Hz (lab) 2 dB gain at 6 Hz; 3 dB gain at 9 Hz (field)	2-3 dB vs. Hyp NOWS	15-20 dB vs. NASA NOWS 4-5 dB vs. Hyp NOWS	2 dB vs. Hyp NOWS	4-5 dB vs. Hyp NOWS
		Box	4-5 dB loss at 9 Hz; 11 dB loss at 18 Hz (lab)	5-6 dB vs. Hyp NOWS	2 dB vs. Hyp NOWS		
	Other WS	Hyp Trampoline Tent	0 dB at 6 Hz and 9 Hz (field)	10-15 dB vs. Hyp NOWS	10-15 dB vs. Hyp NOWS	16 dB at 6 Hz, 13 dB at 9 Hz vs. Hyp NOWS	16 dB at 6 Hz, 13 dB at 9 Hz vs. Hyp NOWS
		ARL Metal Tent	1 dB gain at 6 Hz and 9 Hz (field)	10-12 dB dB vs. Hyp NOWS	10-12 dB dB vs. Hyp NOWS	17 dB at 6 Hz, 18 dB at 9 Hz vs. Hyp NOWS	17 dB at 6 Hz, 18 dB at 9 Hz vs. Hyp NOWS
		ARL Metal Cylinder	0 dB at 6 Hz and 9 Hz (field)	10-12 dB dB vs. Hyp NOWS	10-12 dB dB vs. Hyp NOWS	12 dB at 6 Hz, 16 dB at 9 Hz vs. Hyp NOWS	12 dB at 6 Hz, 16 dB at 9 Hz vs. Hyp NOWS
	Colander	No felt	0 dB at 6 Hz; 1-2 dB loss at 9 Hz (field)	9-10 dB vs. Hyp NOWS	9-10 dB vs. Hyp NOWS		
		With felt	0 dB at 6 Hz; 1-2 dB loss at 9 Hz (field)	9-10 dB vs. Hyp NOWS	9-10 dB vs. Hyp NOWS		
Hyperion Microbarometer with Acorn	SSC-Pac CCF sphere		4 dB loss at 9 Hz; 0 dB loss at 18 Hz (lab) 3 dB loss at 6 Hz; 8 dB loss at 9 Hz (field)			5 dB vs. Hyp NOWS	1-2 dB vs. Hyp NOWS
	CCF sphere + Cylinder		3 dB loss at 6 Hz; 8 dB loss at 9 Hz (field)			15-20 dB vs. Hyp NOWS	12-15 dB vs. Hyp NOWS

This page is intentionally blank.

INITIAL DISTRIBUTION

84310	Library	(1)
85300	Archive/Stock	(1)
56490	R. Plate	(1)
56490	D. Grimmett	(1)

Defense Technical Information Center
Fort Belvoir, VA 22060–6218 (1)

This page is intentionally blank.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-01-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
November 2019	Final	

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Development of a Compact Wind and Water Mitigation System for Deployment of Infrasound Sensors on Unmanned Surface Vehicles.	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	**5d. PROJECT NUMBER**
Randall Plate Doug Grimmett **NIWC Pacific**	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
NIWC Pacific 53560 Hull Street San Diego, CA 92152–5001	TR-3185

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Maritime Infrasound Monitoring project Naval Innovative Science and Engineering (NISE) Program NISE Coordinator: Dave Rees 53560 HULL ST San Diego CA 92152-5001	NISE
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report was completed for the Maritime Infrasound Monitoring (MIM) project. One objective of the MIM project at the time testing was done for this report was to develop a unique windscreen design for deployment with an infrasound sensor aboard a small, unmanned surface vehicle (USV). The unique windscreen must possess several specific capabilities/features: it must (1) reduce wind noise, (2) provide protection from water, and (3) be suitably compact for deployment on a Liquid Robotics SV2/3 USV. This report documents the results of a test performed to evaluate potential windscreen designs that address these requirements.

A side-by-side test event was performed at NASA Langley in Hampton, VA from April 13–20, 2018 to investigate the performance of various infrasound sensors and windscreens. The premise for the test was primarily to investigate the performance of the closed-cell foam windscreens being developed by NASA in terms of transmissivity and wind noise reduction. Additionally, as part of this research, other compact windscreens were evaluated to provide comparison points. These alternative windscreens consisted of two perforated metal windscreens (tent and cylinder) from Army Research Lab, a trampoline fabric tent windscreen from Hyperion Technology Group, and a perforated metal colander provided by SSC Pacific. In addition to the windscreens, two different infrasound sensors were evaluated: an electret microphone being produced for NASA by PCB Piezotronics, and a piezoelectric microbarometer produced by Hyperion.

The results of our testing show that the closed-cell foam windscreens do not attenuate the infrasound signal, provided a properly designed back chamber is used; improper venting results in signal attenuation. Both versions of the closed-cell foam windscreens (those designed for use with NASA microphone and Hyperion microbarometer) demonstrated good wind mitigation performance. However, the tent style windscreens demonstrated slightly better wind mitigation performance at the source frequencies used for this test.

15. SUBJECT TERMS

Infrasound, compact windscreen, unmanned surface vehicle, wind mitigation, water mitigation, closed-cell foam

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Randall Plate
					19B. TELEPHONE NUMBER *(Include area code)*
U	U	U	U	61	1 619-553-2076

Standard Form 298 (Rev. 10/17)
Prescribed by ANSI Std. Z39.18

This page is intentionally blank.

This page is intentionally blank.

Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001